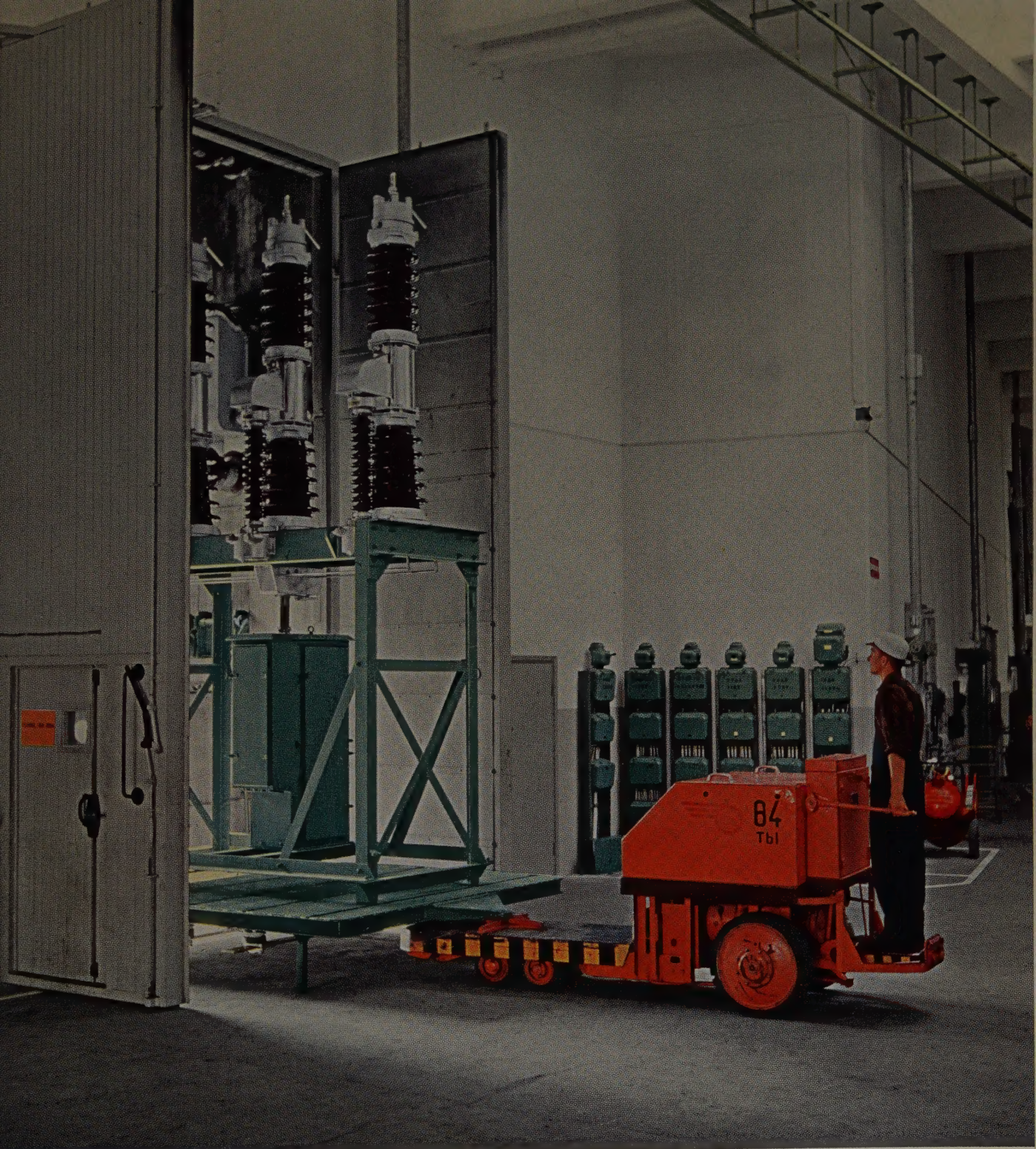


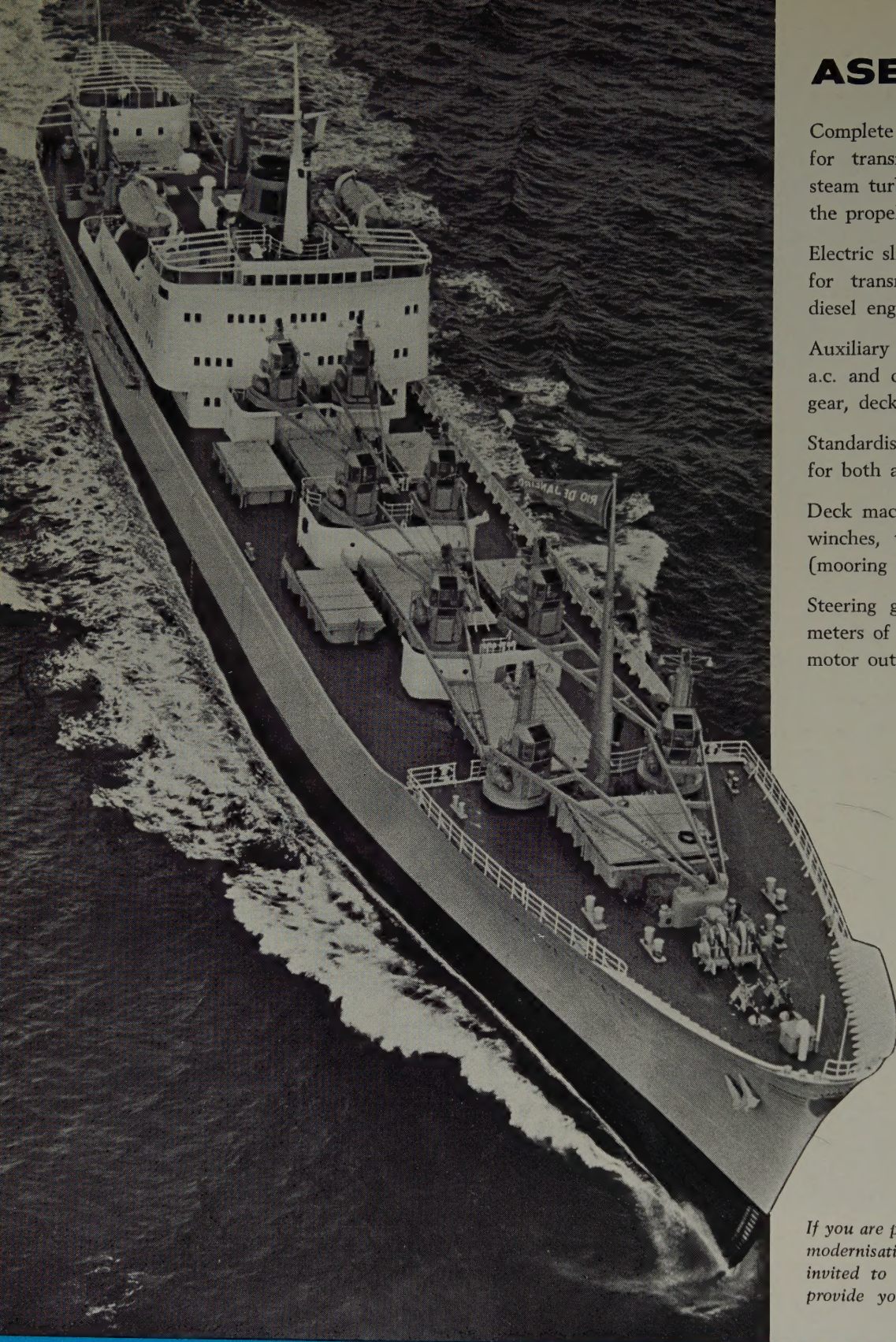


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9

A circuit-breaker mounted on a special trolley being moved into a test cell at the Asea High-voltage Laboratory, Ludvika. (F 479)



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THE NEW ASEA HIGH-POWER LABORATORY AT LUDVIKA

Bertil Thorén, High-power Laboratory, Ludvika

U.D.C. 621.317.2
621.316.5
Asea Reg. 79

The new Asea High-power Laboratory at Ludvika, which was commissioned in 1958, is one of the largest in the world with its two generators having a combined short-circuit power of 3,500 MVA. A description is given of the comprehensive equipment as well as of the measures adopted for rationalising its operation.

Asea's first High-power Laboratory was commissioned in 1933. With its short-circuit test generator of 1,000 MVA (short-circuit power) it was at that time one of the largest in the world, thus making possible considerable advances, above all in the field of circuit-breakers. It was largely due to this laboratory that Asea was able to participate with such success in the development of the Swedish 200 and 400 kV power-line systems. Since then, however, rapid developments have taken place in the field of power engineering, and the ever increasing growth in the short-circuit powers of transmission lines and the consequent increased requirements made particularly on circuit-breakers and transformers resulted in the resources of the laboratory becoming quite in-

adequate. It was therefore decided to build a new, and larger, laboratory, which was formally inaugurated in the autumn of 1958 (Fig. 1). The new Asea High-power Laboratory with its total generating capacity of 3,500 MVA is once more on a level with the largest laboratories in the world.

GENERAL ARRANGEMENT OF THE LABORATORY

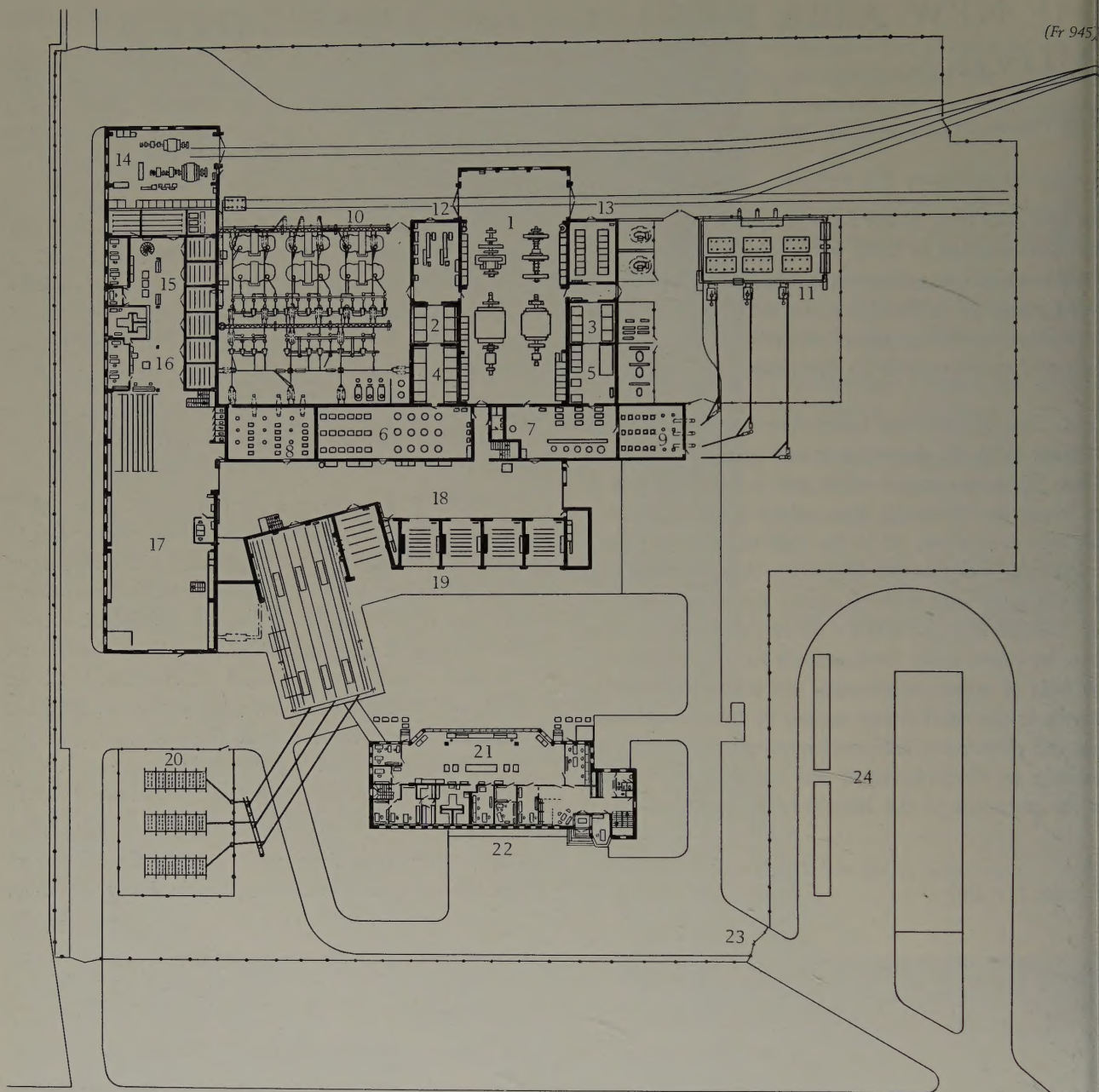
The laboratory stands on a site of approximately 20,000 m² (215,000 sq. ft) and has a total floor area of nearly 6,000 m² (65,000 sq. ft). The planning of the laboratory (Fig. 2) is the result of a compromise between many different requirements. The greatest emphasis has been placed on good communications both within the laboratory and outside. In addition, great attention has been paid to the provision of adequate protection for both the laboratory personnel and the surroundings. This question of protection is particularly important in view of the fact that several tests may be performed simultaneously, independent of one another.

Great efforts have been made to make the running of the laboratory as rational as possible. For this reason,

Fig. 1. General view of the new High-power Laboratory at Ludvika. (Fr 329)



(Fr 945)



- | | | |
|--|--|---------------------------------------|
| 1. Machine hall for high-power generators | 12. Compressor plant | 17. Assembly workshop |
| 2, 3. Switchgear with back-up circuit-breakers | 13. Substation | 18. Assembly workshop and passage-way |
| 4, 5. Switchgear with high-speed making switches | 14. Machine hall for the high-current equipment | 19. Test cells |
| 6, 7. Reactors and resistors | 15. Control room and test cells for the high-current equipment | 20. Capacitor bank |
| 8, 9. Capacitors | 16. Control room and test cells for the mechanical testing of circuit-breakers | 21. Control room |
| 10, 11. High-power transformers | | 22. Offices |
| | | 23. Main entrance |
| | | 24. Car park |

Fig. 2. General plan of the High-power Laboratory. (Fr 945)

the laboratory has been equipped with remote-controlled isolators in the test circuits, special transport trolleys, etc., in the test cells to ensure the rapid replacement of test objects, and special change-over devices in the measuring circuits. In order to relieve the larger generators of all low-power tests, a high-current equipment comprising

two generators with a total rating of approximately 80 MVA has been installed. An article describing the equipment of the new High-current Laboratory, which is located in the premises of the High-power Laboratory will be published in a coming number of the *Assea Journal*. Equipment for the mechanical checking of the circuit-breakers prior to their testing in the high-power test cells has also been included.

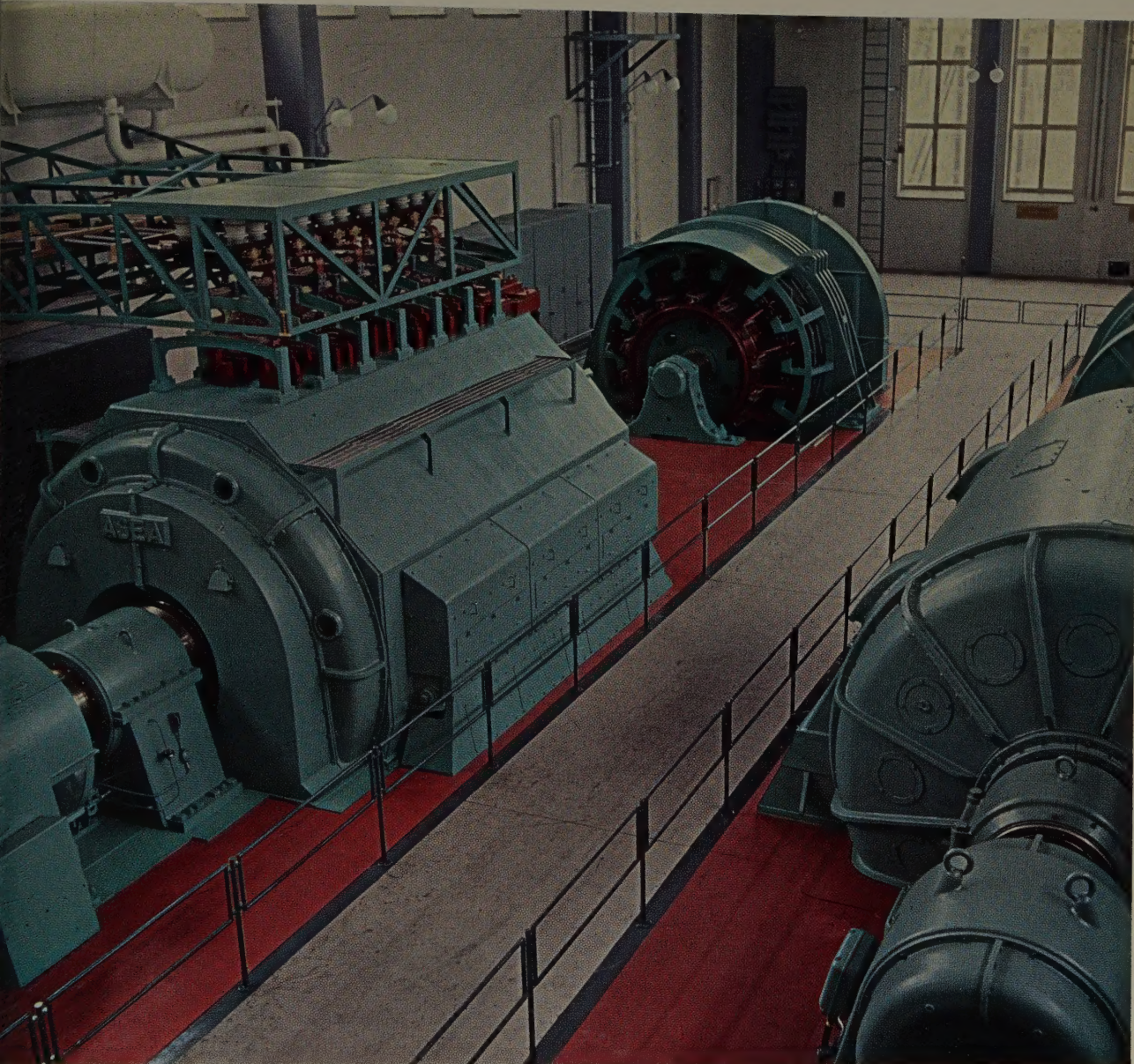


Fig. 3. Interior of the machine hall. To the left, the new 2,500 MVA short-circuit test generator with its exciter (in the background). To the right, the old 1,000 MVA short-circuit test generator with its driving motor (in the foreground). (F 475)

The short-circuit test generators with their exciters are housed in a special machine hall (Fig. 3). The rooms at the sides of the machine hall contain the back-up circuit-breakers, the high-speed making switches and other switchgear. Facilities are also provided here for connecting up reactors and resistors in the high-power circuits. Cables are led from the switchgear rooms both to busbars beneath the test cells and to the high-power transformers. These cables are of concentric design and thus have a low reactance and a very high short-circuit withstand strength. The transformers with their high-voltage switchgear are set up outdoors (Fig. 4) and are connected to a busbar running along the roof behind the

test cells. Capacitors for setting the rate-of-rise of the restriking voltage may also be connected to the busbars. These capacitor banks are housed in separate rooms. In addition, there is also a larger capacitor bank (Fig. 5) mounted outdoors and intended for use in conjunction with capacitive breaking tests.

The reconnections in the high-power circuits are effectuated to a large extent with the aid of isolators, which are motor-operated and are controlled from a desk in the operating room (Fig. 6). The pilot switches are mounted in a mimic diagram on part of the control desk and are combined with indicators. It is thus always possible to exercise full control over the switching and, furthermore, make a rapid reconnection between two tests.

A wide passage-way has been provided in order to facilitate communications between the workshop and the test

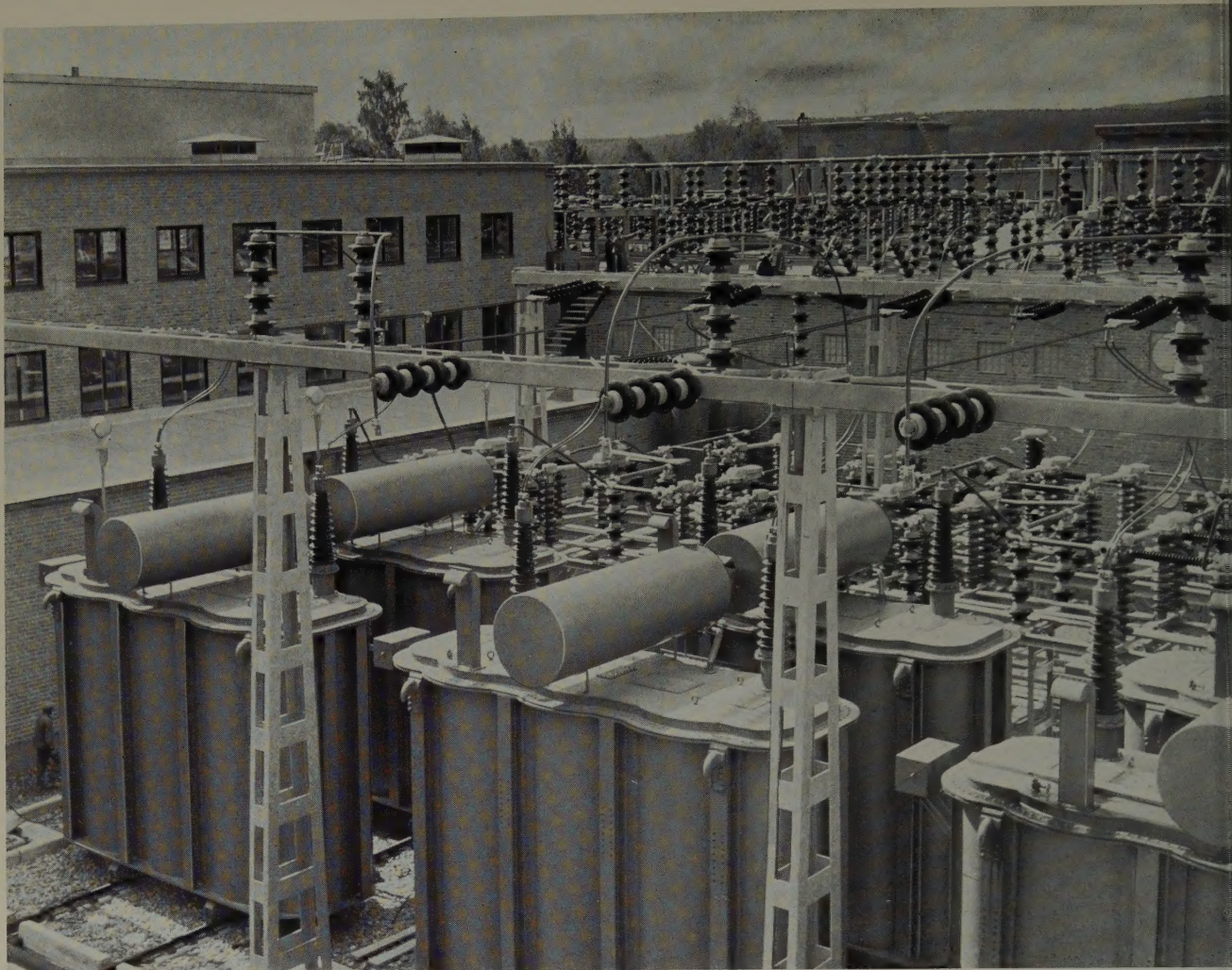


Fig. 4. The high-power transformers. The bank comprises six single-phase units with a total short-circuit power of 9,000 MVA. Behind the transformers a glimpse can be had of the high-voltage switchgear and, on the roof, in the background, the high-voltage busbar. (51065)

cells. It is thus possible to reach the test cells from behind, which is of considerable importance from the safety viewpoint and meets the requirement for undisturbed service when several tests are being performed simultaneously. The objects under test are assembled in the workshop on special trolleys, fitted with the necessary control and measuring equipment. After assembly, the test object first undergoes a mechanical check to see that all the operations are correctly adjusted, and then it is moved out to one of the test cells (see the illustration on the cover). Facilities are provided in the test cells for the rapid connection of the test object to the high-power, the control, and the measuring, circuits. The passage-way is also used as an assembly site for smaller test objects. The system described above makes possible rational service in that the test objects need not remain in the test cells longer than is necessary for the performance

of the test itself. The circuit-breakers for the highest voltages cannot however be transported in this manner, but are assembled direct in one of the larger test cells.

An underground passage, which can also be used by the personnel, provides the necessary communication between the office building and the rest of the laboratory. It is thus unnecessary for anybody to remain above ground between the office and the test cells and run the risk of being hit by splinters from test objects. A railway track, dimensioned for heavy loads and with unloading facilities in the machine hall, as well as a road leading into both the workshop and the passage-way, are provided for communication with the outside world. The railway track is also used as a test site when testing large transformers and reactors. At the northern end of the machine hall there is a hoist with a lifting capacity of 200 tons, which can be used for inspecting the transformer core and windings after a test.

The laboratory is supplied with electricity from the distribution station of the Ludvika Works via 10 kV cables. The voltage is distributed within the laboratory

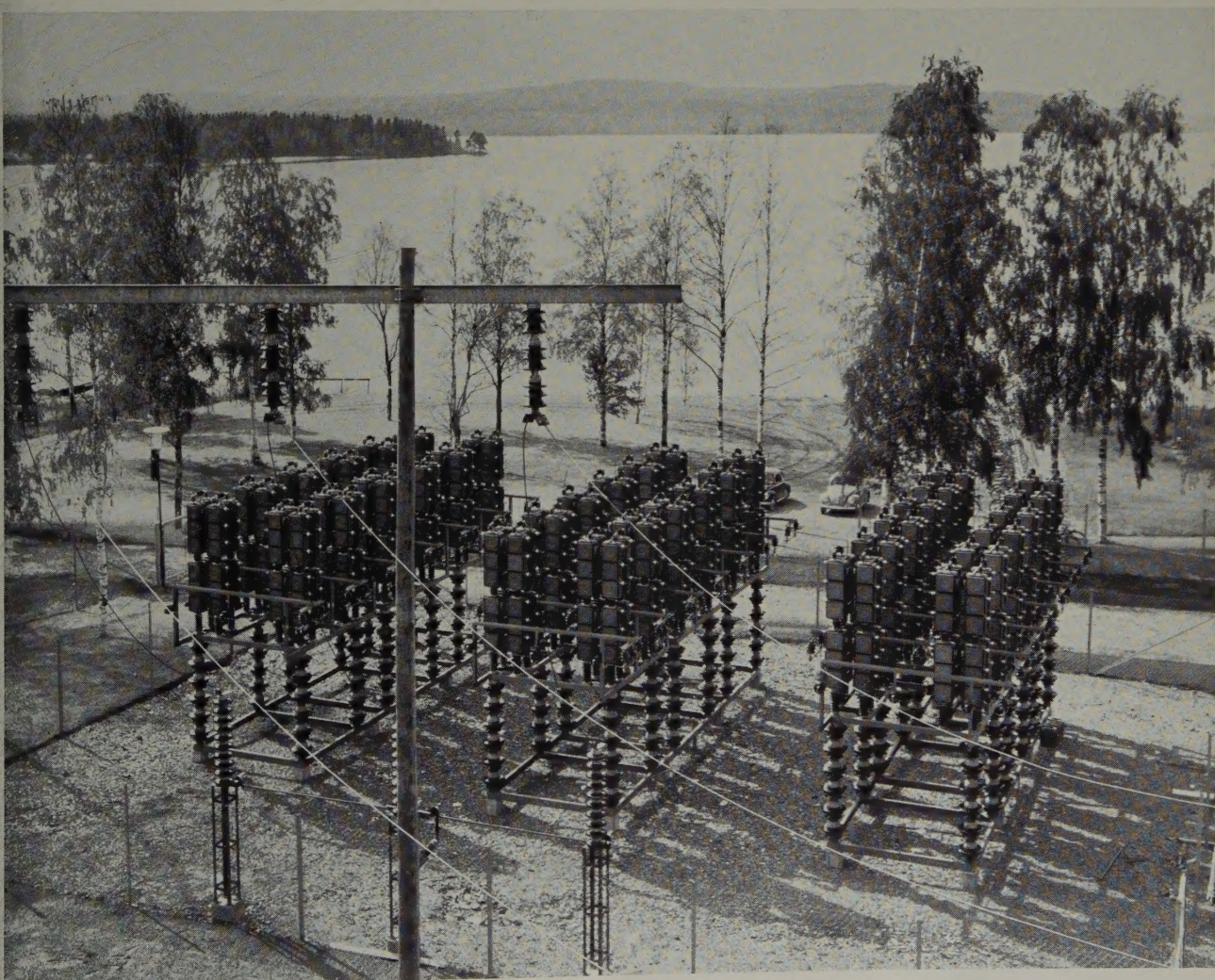
at 3.3 kV, 400 V and 220 V. Auxiliary power for excitation, control, indication, etc., is generated by a number of rotary converters and accumulator batteries charged via rectifiers. The laboratory also has its own compressor plant for supplying compressed air. The permanently installed circuit-breakers within the laboratory are supplied at a constant pressure of 15 atm gauge. There are several automatically regulated systems for the test cells and these can be adjusted for maintaining a constant pressure of up to 20 atm gauge. In addition, there is a system which is fed direct from a compressor at a pressure of 30 atm gauge. The laboratory is equipped with two pressure-oil systems, one for summer, and one for winter, oil, for the rapid charging of oil circuit-breakers. Discharge points are arranged in the test cells, the transport passage-way and the assembly workshop. These discharge points are fitted with coiled-up hoses having nozzles. The used oil from the circuit-breakers is drained via hoses into special sumps.

Fig. 5. The 21.6 MVA capacitor bank for capacitive breaking tests. This bank is built up of, in all, 864 capacitor units. (51864)

HIGH-POWER EQUIPMENT

The high-power equipment of the laboratory has been designed to produce a short-circuit power of approximately 2,000 MVA behind the transformers (symmetrical breaking capacity after a short-circuit time of 0.2 s). This base power is supplied by a generator having a nominal rating of 2,500 MVA together with a transformer bank of 9,000 MVA. By running this generator in parallel with the 1,000 MVA generator from the old laboratory, it is possible to attain an output of as much as 2,500 MVA (behind the transformers). The general data of the equipment are given in Table 1, and the curves in Fig. 7 show the breaking capacity available as a function of the recovery voltage.

Both the generators are of the turbo type and have been specially designed owing to the severe demands made on low reactance and high short-circuit withstand strength. The continuous load-carrying capacity is thus considerably less than is indicated by the frame size of the machine. The generators have no damping windings. Furthermore, the rotor surface is designed with deep slots to prevent the occurrence of any eddy currents.



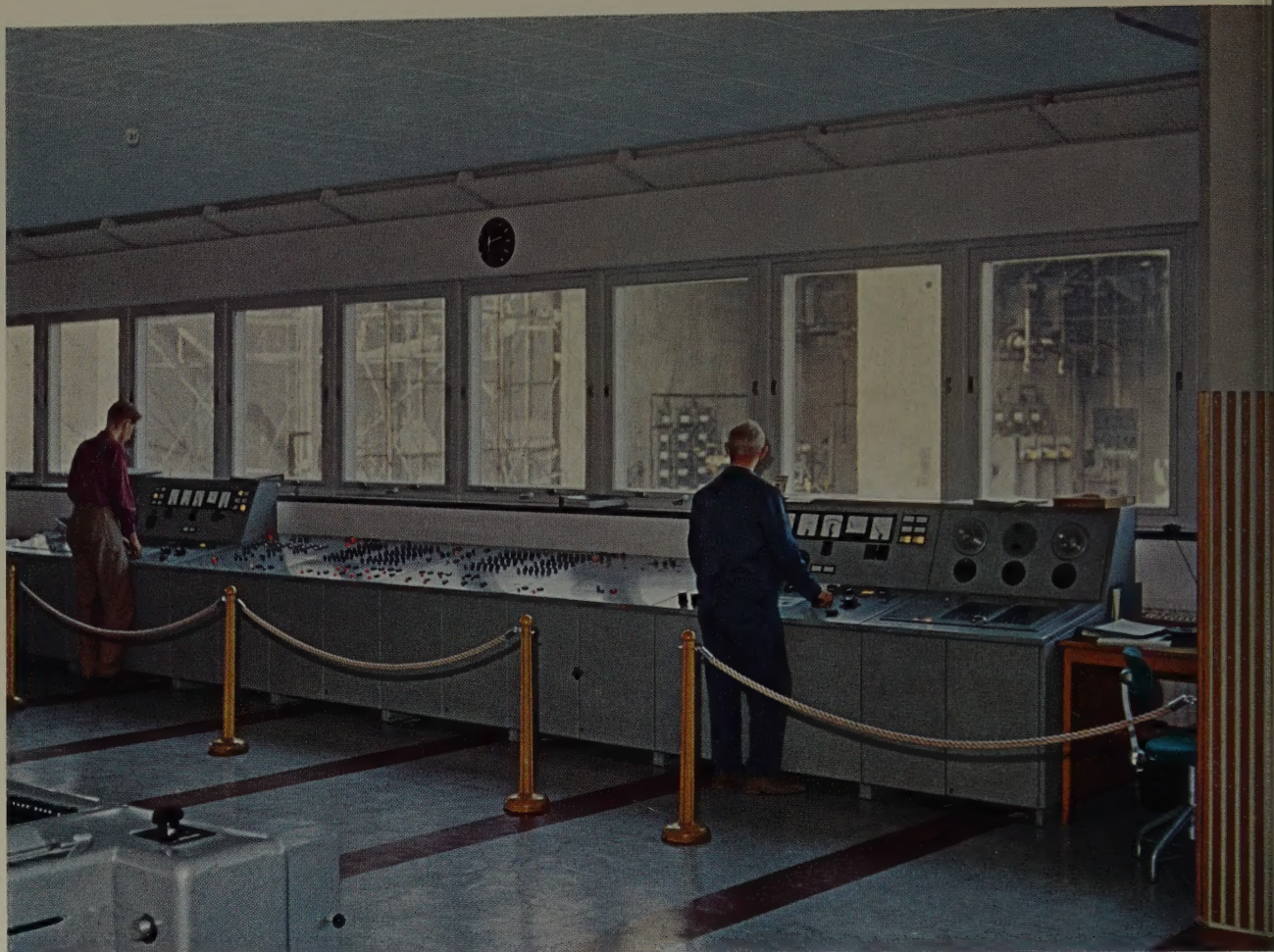


Fig. 6. The control room. At the sides, the control desks with synchronising gear and sequence controller. In the middle, the mimic diagram of the testing plant, containing pilot switches for remote operation and position indication. (F 478)

The subtransient component of the short-circuit current is therefore only slightly larger than the transient one. The absence of any real damping circuits results in the flux, and consequently the recovery voltage, rapidly attaining the no-load value after a short circuit. It will then also be possible to maintain the short-circuit current practically constant by means of a pronounced super-excitation. This means that the breaking power which can be taken out will be independent of the length of the short-circuit time and that, in the case of, for example, high-speed reclosing tests, it will be possible to attain practically the same power for both interruptions.

The flux density in the core is high for both machines, which signifies that full voltage cannot be permitted over a longer period. When employing "flying excitation", this nevertheless does not constitute any drawback. The extremely high short-circuit currents, and their associated large leakage fluxes across the stator

teeth, will also mean that the machine reactances will be very much dependent on saturation. At high excitation the actual short-circuit powers of the machines will therefore be considerably greater than the reactance values for non-saturated machines would appear to indicate. The actual short-circuit power of the largest generator amounts, for example, to more than 3,000 MVA at full voltage. This high power is not, however, utilised direct, since it is accompanied by large mechanical stresses. Nevertheless, in the case of, for example, the taking out of power across transformers, the low reactance lying behind will indirectly serve a useful purpose.

The generator sets are started with the aid of automatically operated contactor-type starters. These are also connected up during short-circuit tests to prevent excessive shocks on the network, and are employed as loading resistors during the electrodynamic breaking of the sets. The starters are utilised furthermore when the machines are run at other frequencies than 50 c/s. This is done quite simply in such a way that the machine, after having been run up to a value slightly in excess of the desired frequency, is disconnected from the network and then reconnected when the frequency has dropped

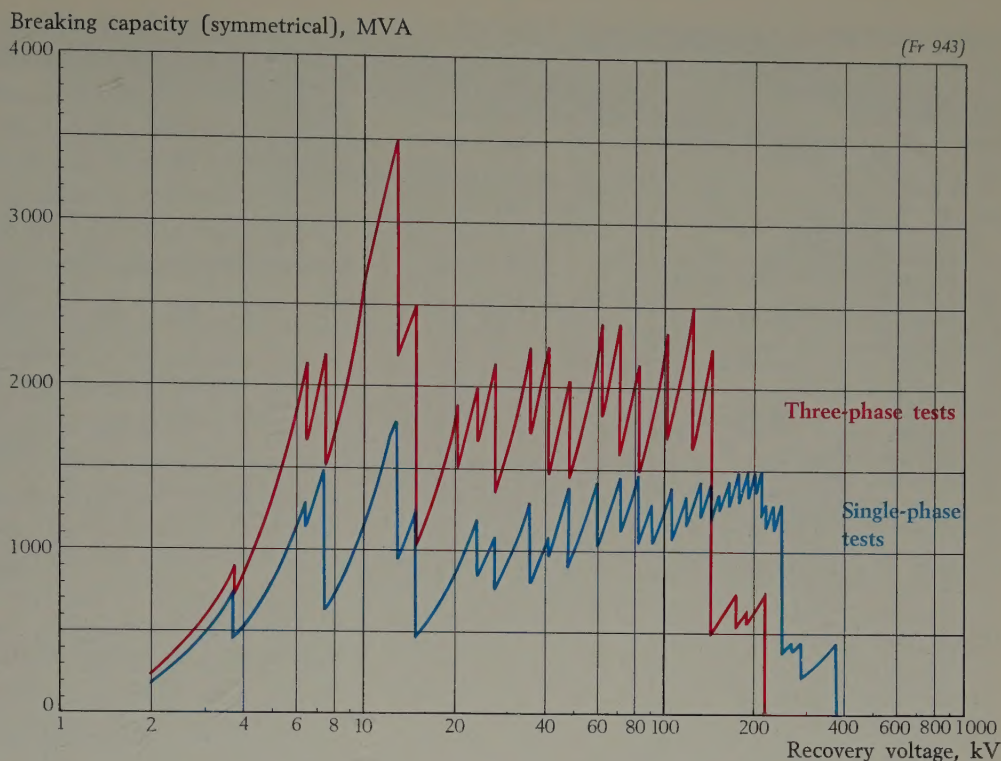


Fig. 7. The breaking capacity (symmetrical) available after a short-circuit time of 0.2 s as a function of the recovery voltage. (Fr 943)

to a value slightly below the set frequency, and so on. Short-circuit tests are performed while the speed of the machine is dropping.

The machines have closed cooling systems with means for bringing into action a CO₂ battery in the event of fire. The tripping impulse is given by flame relays having nitrated filaments and by thermal relays with fuse wires. The machines also have over-voltage protection, over-current protection (by-passed during short-circuit tests), earth-fault protection for both the stator and the rotor and equipment for supervising the bearing and winding temperature, the pressure of the bearing oil, the flow of cooling water, etc. When the protections operate, they trip the associated back-up circuit-breaker and suppress the generator field. In the event of more serious faults, fire, or the like, the affected set is also automatically retarded.

The exciters are separately driven and provided with a flywheel. They are capable of supplying a considerable super-excitation during the short-circuit tests. The machines are designed with a laminated stator and a special rotor winding because of the high currents which are to be commutated. The exciter protections include an earth-fault protection, and a balanced-beam relay operates for any flashovers on the commutator.

The transformer banks each comprise six single-phase units. Single-phase transformers have been selected, partly out of consideration for the transport weight and partly because higher voltages and powers can be obtained with single-phase tests. The highest voltage at

which the full three-phase power can be attained is 144 kV. It has not been considered justifiable to employ a higher voltage, since the circuit-breakers manufactured by Asea for higher voltages always have several series-connected breaks. When testing such circuit-breakers, the test must in any case be limited to individual breaking units because of the limited power available. Facilities are provided nevertheless for connecting in series the high-voltage side of all the transformers in bank 1, thereby coming up to 250 kV, single-phase. For reasons of insulation the mid-point of the transformers is then earthed. Furthermore, the transformers in bank 1 enable tests to be performed with limited power at voltages up to 220 kV, three-phase, and 380 kV, single-phase, with the mid-point being earthed in the latter case.

Curves like those illustrated in Fig. 7 have been the decisive factor when selecting the winding voltage and the number of windings per phase on the high-voltage side. It has been found that six to eight windings per phase will satisfactorily cover the voltage range in question. The six-winding alternative was selected for the larger transformers (bank 1) with three windings per transformer unit, since it was found suitable to design these transformers, from the point of view of the mechanical strength, as five-limb core transformers (three wound limbs). The transformers in bank 2 are of more conventional, two-limb design and thus have four windings per unit. The winding voltage of the new transformers has been selected so as to enable the highest possible output to be obtained at the standard voltages recommended by the I.E.C.

Table 1. Data for the high-power equipment

Generators	Set 1	Set 2
Type	GTB 2142	GTB 1938
Nominal rating ¹ , MVA	180	130
Frequency, c/s	50	50
Speed, r.p.m.	1,500	1,500
Rated voltage, kV	7.5/13/15/(26) ²	3.75/6.5/7.5/13
Rated short-circuit power ³ , MVA	2,500 ⁴	1,000
Reactance at three-phase short circuit when connected for 13 kV (non-saturated machine)		
synchronous reactance, ohms/phase	0.65	1.3
transient reactance, ohms/phase	0.076	0.18
subtransient reactance, ohms/phase	0.070	0.16
breaking reactance ⁵ , ohms/phase	0.073	0.17
Max. permissible no-load running time at service voltage, min	10	25
Weight of stator, tons	143	105
Weight of rotor, tons	90	66
Rotor diameter, mm	1,700	1,550
Rotor inertia (WR ²), ton-metres ²	30	20
Driving-motor output, kW	3,000	1,000
Exciters	Set 1	Set 2
Type	LC 2305	LA 218
Continuous output, kW	6,500	3,000
Speed, r.p.m.	428	428
Rated voltage, V	1,050	1,000
Rated short-circuit current ⁶ , kA	27	9.75
Max. permissible peak current at short circuit, kA	60	15
Inertia (WR ²), ton-metres ²	57.5	25
Driving-motor output, kW	600	2,200 ⁷
Transformers	Bank 1	Bank 2
Type	TTTY 10500	EO 89 EO 94
Number of single-phase units	6	3 3
Nominal rating ¹ , MVA	66.7	33.3 33.3
Weight per unit, including oil, tons	154	85 76
Number of high-voltage windings per transformer unit	3	4 4
Winding voltage, kV	24/√3	22/√3 33/√3
Basic insulation level, kV	625	450 325
Max. voltage, three-phase, kV	144	220
Max. voltage, single-phase, kV	250	380
Short-circuit power (inherent), MVA	9,000	3,000
Reactors	Set 1	Set 2
Number of unit per phase	4	5
Reactance per unit (50 c/s), ohms	0.03	0.051–2.11
Setting range (50 c/s), ohms/phase	0.075–0.12	0.033–3.9
Resistors	Set 1	Set 2
Number of units per phase	6	3
Resistance per unit, ohms	0.04	0.04 ⁸
Setting range, ohms/phase	0.0067–0.24	0.0045–0.12
Capacitors	Bank 1	Bank 2 Bank 3
Number of units per phase	38	24 288
Setting range ⁹ , μF/phase	0.004–130	0.004–130 2.5–360
Max. service voltage, kV	144	132 165
Total nominal rating, MVar	3.15	1.8 21.6

¹ Continuous load-carrying capacity for the conventional design of the machine type. The actual load-carrying capacity is considerably lower because of the special design.

² The machine is insulated for 15 kV. When connected for 26 kV, it is only used for tests at 25 and 16²/₃ c/s.

³ Symmetrical breaking power available after a short-circuit time of 0.2 s.

⁴ Applies to short circuit without d.c. component in any of the phases. With full asymmetry in any phase, max. 2,250 MVA can be permitted. The limit is set by the mechanical stresses imposed on the winding.

⁵ Ratio between recovery voltage (phase voltage) and breaking current, measured according to the stipulations in the circuit-breaker standards.

⁶ For 0.2 s.

⁷ The motor is greatly over-dimensioned.

⁸ Two units per phase are divided into two similar groups, which can be connected in series or parallel.

⁹ With standard connection. When special connections are used, higher capacitance values may be obtained.

The maximum flux density in the core has been set to a relatively low value, since difficulties will otherwise be encountered due to d.c. excitation from high arc voltage or due to inrush currents when switching in the transformers at no-load. The transformers in bank 1 have built-in, remotely operated isolators for reconnecting the high-voltage windings. All the transformers are fitted with gas relays which give a signal in the event of a fault.

Each generator is provided with a set of current-limiting reactors and a set of resistors for adjusting the power factor. The reactors are built up as concrete units without any iron core and are designed to withstand the highest currents to which they are likely to be exposed. They permit the output of the larger generator to be regulated down to about 1,000 MVA, and that of the smaller generator down to about 40 MVA, in steps of, on the average, 10 per cent. The resistors, which are built up of cast-iron grids, are intended to increase the power factor from the inherent value of the plant (approximately 0.05) to the maximum value (0.15) permitted in the circuit-breaker standards. Their range is sufficient to permit regulation down to an output of about 100 MVA and they can be adjusted in most cases in steps of 10–20 per cent.

The two capacitor banks for setting the rate-of-rise of the restriking voltage are associated in principle with their own generator-transformer unit and enable the r.r.r.v. to be reduced to about 150 V/μs at 35 kV and 600 V/μs at 130 kV. These values are sufficient for normal tests. If the r.r.r.v. is to be reduced still further, the third capacitor bank, which is normally employed for capacitive breaking tests, can be used.

OPERATING EQUIPMENT

The back-up circuit-breakers are of six-pole design (two poles per phase) and each pole is connected to its own generator winding. This means that the switching conditions will be the same irrespective of the manner in which the generators are connected. At the same time, the different generator windings will be isolated from one another after interruption and consequently there will be less risk of damage arising due to double earth faults and the like. The breaking capacity is 60 kA/pole at 13 kV. The circuit-breakers are of air-blast type with their contacts placed inside pressure chambers.

The high-speed making switches are used for closing, particularly synchronous closing, of the test circuits. They have three poles which are individually operated. The contacts are maintained continuously under pressure from compressed air, which results in a short contact travel, rapid closing, a minimum of pre-arcing and insignificant contact wear due to burning. The making

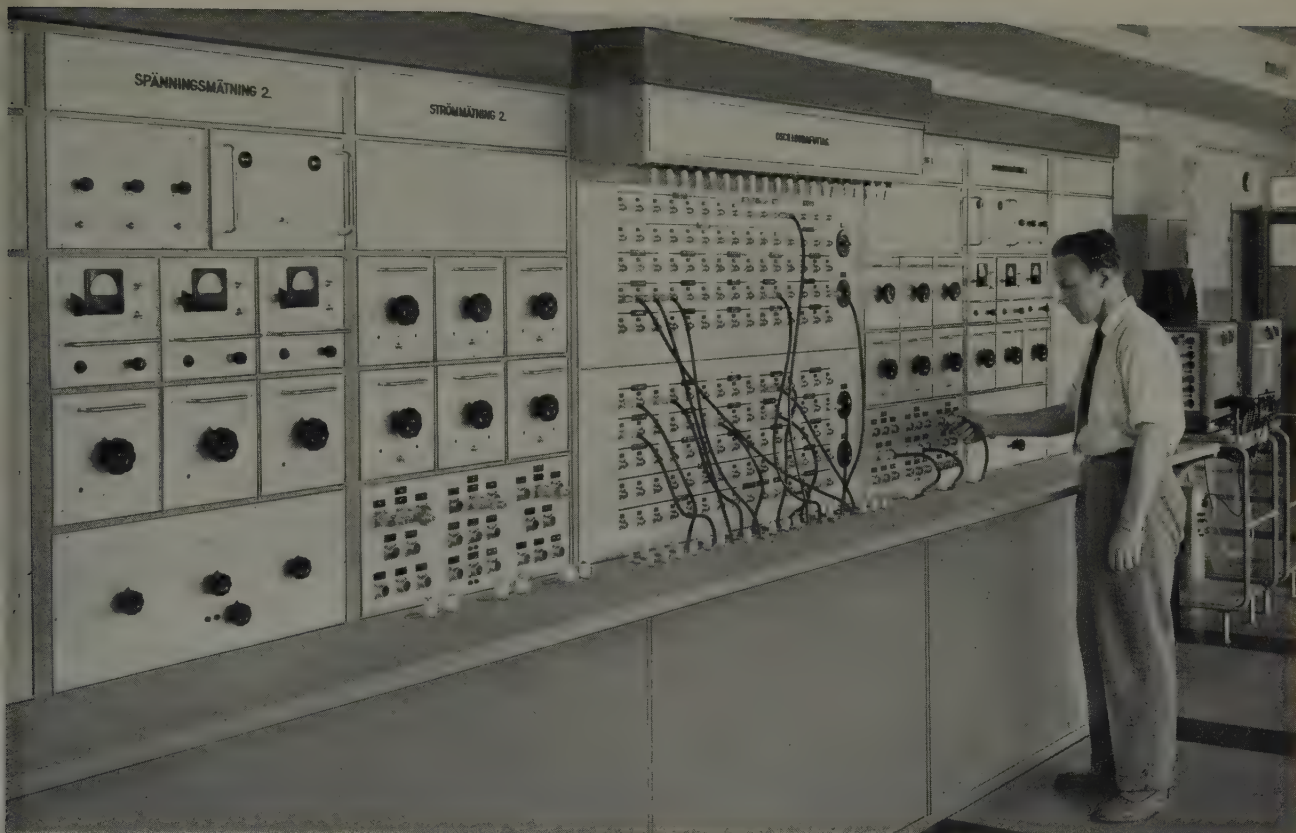


Fig. 8. The measuring board. In the panels at each side, the constant selectors, etc., for voltage, current and power measurements. In the central panel, the plug board for connecting up the oscillograph elements. (53593)

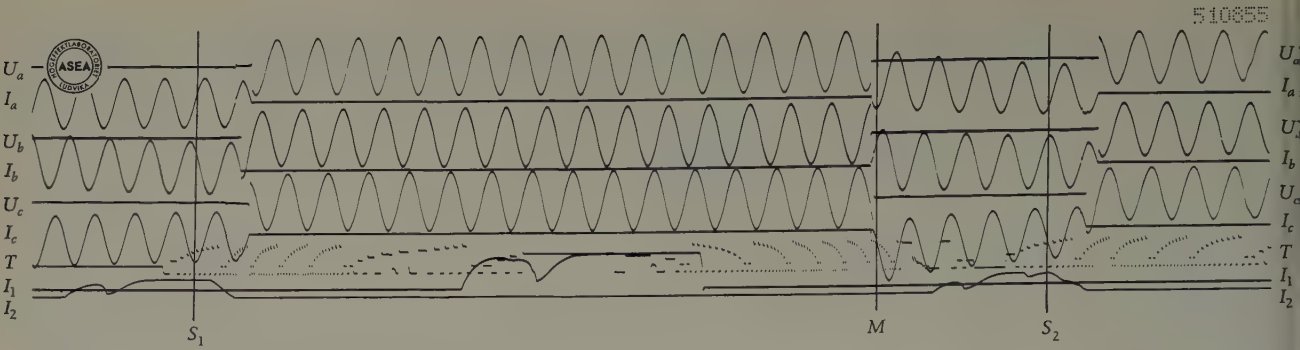
capacity is 300 kA (peak value) at 15 kV and the accuracy is better than ± 5 electrical degrees (50 c/s).

A more detailed description of the back-up circuit-breakers, the high-speed making switches and the isolators will be published in a future number of the Asea Journal.

All the necessary operations for the tests are performed from control desks (Fig. 6), one being provided for each generator. Each control desk contains a simple diagram with built-in pilot switches for the field circuit-breaker, the back-up circuit-breaker, the high-speed making switch, the test circuit-breaker, etc. It also includes setting knobs and instruments for the exciter voltage, the generator voltage and speed, the operating voltage for the test circuit-breaker, etc., as well as a loud-speaker system for the test cells and the machine hall. A rotary sequence controller is employed for controlling rapid sequences. This controller is fitted with a device which ensures that it always completes a revolution when once initiated and thus does not stop in an intermediate position. A change-over switch is used for selecting the type of operation. It can be set to "Manual

operation", where all the outgoing circuits are disconnected from the sequence controller, which then can be adjusted manually for setting the operating times, etc. When in the position "Indications", all the high-power circuits are disconnected, but the test circuit-breaker, oscillographs, etc., remain connected up. When in the position "Short-circuit running", all the circuits are connected up to the sequence controller. Finally, when in the position "Continuous running", the sequence controller is fully disconnected, and all operation takes place manually from the control desk.

The setting accuracy of the sequence controller is approximately 0.01 s. When greater accuracy is required, for example, for synchronised closing, the tripping signals are transmitted via special synchronising devices also located in the control desk. Such a synchronising device consists, in principle, of a synchronous motor with a rotatable stator, fed from a pilot generator coupled to the shaft of the high-power generator. This synchronous motor has two contacts on its own shaft with individually adjustable angular positions, which permits, for example, three-phase closing with symmetrical current in all three phases. The outgoing signals are amplified in electronic units, which also contain the necessary blocking devices and which co-ordinate the interrelated time sequence between the outgoing signals. The system is so designed that the high-speed making switch and the test circuit-breaker can be synchronised with one another, which



Symbols	Test values
U_a, b, c – Phase voltage	1st B M 2nd B
I_a, b, c – Phase current	
I_1 – Closing impulse	Breaking current kA (symmetrical) 18.6 — 18.8
I_2 – Trip impulse	Recovery voltage, kV 75.0 — 70.5
T – Contact travel	Peak making current, kA — 52.7 —
M – Instant of contact make	Applied voltage, kV — 80.0 —
$S_{1,2}$ – Instant of contact separation	Breaking capa- city, MVA (symmetrical) 2,420 — 2,300

Fig. 9. Oscillogram from a high-speed reclosing test (B-MB) on an oil-minimum circuit-breaker. (Z 11170)

is of great importance when performing, for example, asymmetrical tests.

A system employing “flying excitation” has been adopted in order to achieve a constant short-circuit current while the short circuit lasts. This means that, shortly after the exciter has been connected in to the generator field winding, the generator is short-circuited while the generator field is still rising. The excitation will thus increase during the period of the short circuit, and, when correctly set, this increase can be made to compensate the demagnetising effect of the armature reaction. At the same time as the short circuit is interrupted, the field current of the exciter is reversed in order to prevent the generator voltage from rising significantly above its set value. It should be noted that the conditions during the period of the short circuit, in an otherwise similar state, will be the same for this method of flying excitation as for that of super-excitation, where a series-resistor lies in the field circuit. When this resistor is short-circuited, the generator voltage strives to increase according to exactly the same curve as for flying excitation. The main difference between the two methods is that with the series-resistor in the field it is possible for the generator to be excited to the desired voltage before the actual test. When using flying excitation, on the other hand, it is possible to avoid the losses occurring both in the generator and the series-resistor, and, furthermore, the costs entailed in the installation of the latter will be

eliminated. It is not necessary either in the case of flying excitation to design the generator to run at full voltages for any lengthy period.

The system with flying excitation entails certain complications when the two generator sets are run in parallel, since the main exciters cannot be used for synchronising. The problem has been solved, however, with the aid of a pair of pilot exciters, by means of which the generators are excited up to a few kV. They are then synchronised across a synchronising reactor. Immediately before a test is to be commenced, the pilot exciters are disconnected, after which the main exciters can be connected in and the system with flying excitation utilised. Experience has shown that this system is very satisfactory in practice. The fact that the two test generators differ from one another both electrically and mechanically has not led to any difficulties during parallel running. Even high-speed reclosing tests have been successfully performed.

MEASURING EQUIPMENT

The routine measurement of voltages and currents is performed with the aid of resistance voltage dividers and shunts. Capacitive compensation has been adopted for the voltage dividers, which enables them to record satisfactorily frequencies of up to 50 kc/s. The shunts are of coaxial design. The voltage dividers and shunts are provided with constant selectors for choosing the desired range, which obviates the need for re-calibrating the oscillographs between two tests. Special arc-voltage amplifiers are also connected to the voltage dividers and enable the arc voltage to be recorded, while protecting at the same time the oscillograph elements against overloads when the supply voltage returns after an interruption. The amplifiers are also utilised for supplying the power-measuring elements.

Fixed equipment with resistor-type indicators is employed for the routine measurements of motion, e.g., contact travel and piston travel for circuit-breakers. Similarly, special devices for indicating contact separation have been included. Capacitive, inductive and piezo-electric gauges are used for measuring pressures in

circuit-breakers during an interruption. The capacitive gauges are intended for the standard measurements, a frequency-modulated transmission being used for the measuring values. The standard measuring equipment has been assembled in a measuring board in the control room (Fig. 8). The oscillograph elements can be connected up on the plug board in the middle of the measuring board for the desired measurements.

The laboratory possesses a number of electromagnetic and cathode-ray oscillographs of different types. Fig. 9

shows an oscillogram recorded from a standard high-speed reclosing test (B-MB) on an oil-minimum circuit-breaker. In addition, comprehensive photographic equipment is available, including a high-speed camera providing distinct pictures with up to 8,000 pictures/s, and a sweep camera for speeds of up to 4 mm/ μ s. Schlieren equipment for studying air-flow conditions is also available. This equipment comprises flash lamps, appropriate tripping and delaying devices and a high-speed shutter having an exposure time of only 0.03 μ s for studying phenomena during extremely short intervals.

HIGH-VOLTAGE D.C. POWER TRANSMISSION

Uno Lamm, Electrotechnical Development Departments, Västerås

U.D.C. 621.315.051.2.025
Asea Reg. 730

Translation of an article in Teknisk Tidskrift 90(1960):1, pp. 1-6

The article deals with the converters, the converter stations, a d.c. power transmission system as a whole, the overhead lines and cables for direct current, the operational experience and the economics.

The high-voltage d.c. transmission scheme from the Swedish mainland to Gotland which was put into service about six years ago is still the only transmission scheme of its kind in the world which is in practical commercial operation. This may seem strange for a transmission method which was the only one known and used in the early days of electrical engineering.

However, several projects are now under development, the most advanced of which is the 160 MW Cross-channel transmission scheme linking the British and French grids. Asea obtained orders for the essential equipment for this scheme at the beginning of 1958. In Russia, development work started by the Germans during the war has been continued, and work on a 375 MW, d.c. transmission scheme with a 500 km overhead line between Stalingrad and Donbass is progressing.

The reasons for the predominance of the a.c. system are well known. The main one is the simplicity of transformation to various voltages. This is essential for the creation of a rational distribution system and it gives the a.c. system a clear advantage. However, it has always been patent that the transmission line itself is more economical if operated with d.c. This is particularly the case with submarine or underground cables, but it applies to overhead transmission lines too. The possibility of a return to d.c. for long transmission lines has also depended entirely on the development of equipment for converting a.c. into high-voltage d.c. and vice versa.

If it is possible to produce the converters needed at both ends of a d.c. transmission line, and if the cost is known, it is possible to calculate the critical line length, which differs for cables and overhead lines, at which the total costs of the terminal equipment and the line (including the capitalised cost of losses etc.) are equal, that is, the length beyond which the d.c. system becomes the more economical one. Although the results of such calculations depend to a very high degree on local circumstances, general estimates have been made, one of which will be referred to in the present article. At times, however, the d.c. system offers certain technical advantages which may justify its application even in cases where the above-mentioned total cost is not lower in itself.

Now that the d.c. system has been roughly placed in its context, it may be of interest to mention something of its technical characteristics seen in the light of developments during recent years.

THE CONVERTERS

At the transmitting end of the d.c. line, rectifiers are required for converting the a.c. of the generating plant into high-voltage d.c. and, at the receiving end of the line, inverters are needed for reconversion. They are static devices, with conventional transformers for the conversion of the alternating voltage, connected to mercury-vapour-filled electronic valves (Fig. 1). In these devices, the current paths are periodically switched in synchronism with the three-phase current so that they form a smoothly flowing direct current in the trans-

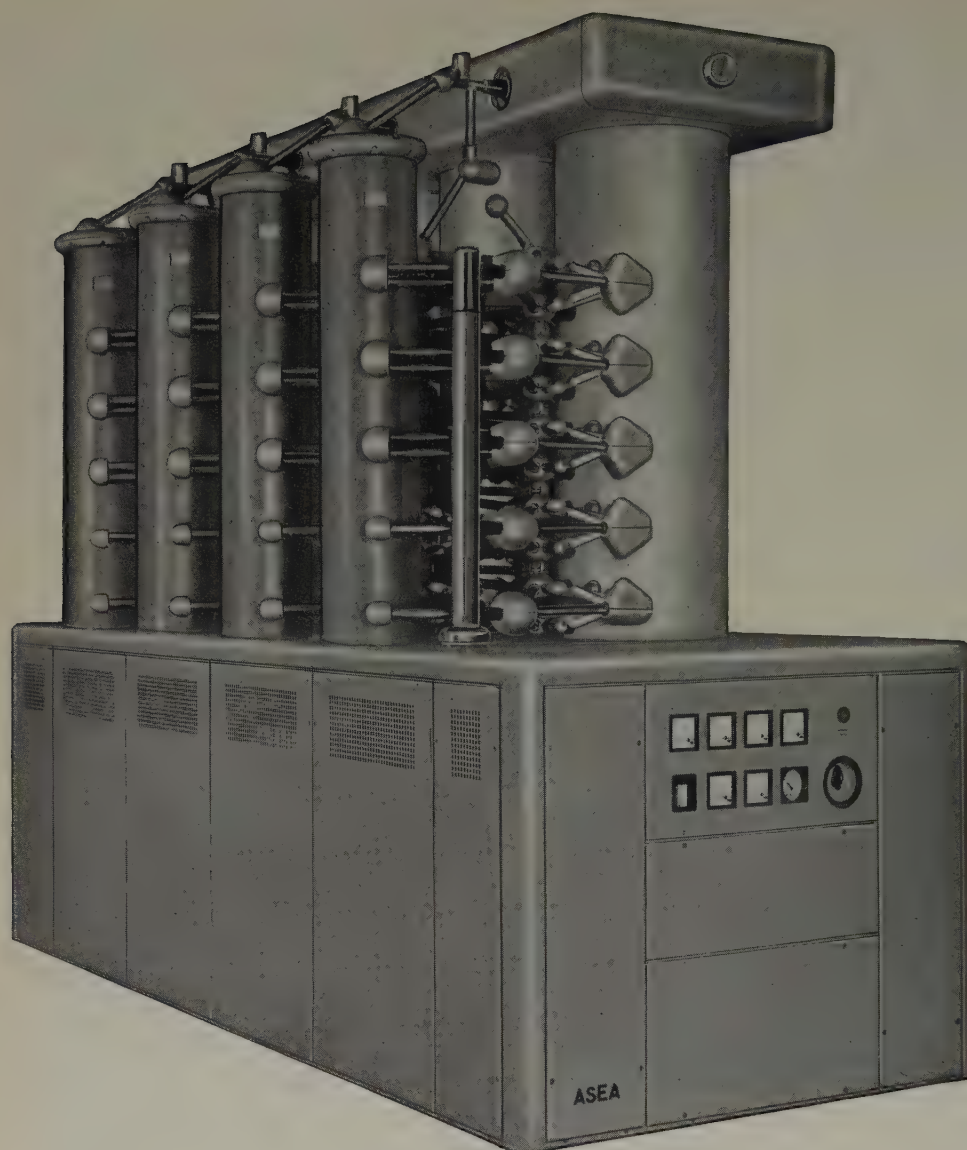


Fig. 1. 100 kV, 800 A, four-anode valve designed for the Cross-channel transmission scheme. (54 663)

mission line. This process can be controlled and regulated by means of control grids in the valve.

Behind the development of these mercury-arc valves capable of operating at the high voltage and current values needed for the transmission of power, there is a great deal of comprehensive and expensive work, much of it empirical.

In view of the remarkable properties displayed by modern semi-conductor type valves, including adaptability to grid control, the question arises as to whether they will supersede mercury-arc valves in the course of time. However, in view of the high voltages which are needed here, the answer is bound to be that no such possibility is yet in sight. Mercury-arc converters, that is, rectifiers and inverters with mercury-arc valves, have gained a position within this field which is likely to remain unchallenged for a long time. The six-pulse double-way connection is the usual one for a converter

designed for power transmission (Fig. 2). It offers advantageous utilisation of the transformer and gives a peak inverse voltage on each of the fixed valves about 1.2 times the full-load voltage between the d.c. poles

The converter is, of course, more intricate and expensive to manufacture and install than the simple a.c. transformer, but it provides new possibilities of rapid and accurate control and regulation. The control grids in the mercury-arc valves make it possible to determine when a valve in a valve group strikes and thus also the moment when commutation from one phase to the next can begin. By this means, it is possible to regulate the ratio between the direct and alternating voltages from a maximum value down to zero and through zero to an almost equally high maximum value of the opposite polarity. An entire regulation process of this kind can be completed in a time of only 0.01 seconds. After the reversal of polarity, the converter operates with a reversed direction of power flow, that is to say, as an inverter,

since the current still flows in the same direction as previously.

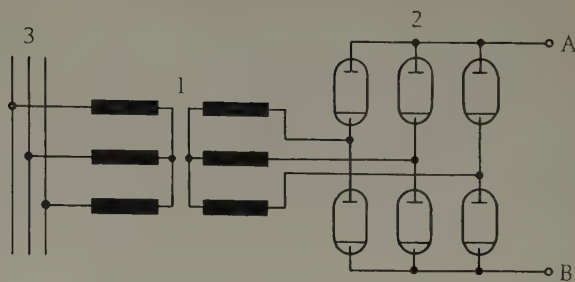
It is also possible to switch the current on and off with the grid without the use of a circuit-breaker. Thus, when switching off, all the valves are blocked. Commutation is then entirely interrupted and those valves which were carrying current at that moment are extinguished as soon as the transformer voltage changes polarity and has forced the current down to zero.

What then is the present-day capacity of these static converters as far as power and voltage are concerned? In the Gotland scheme, which was inaugurated in 1954, 20 MW at 100 kV, d.c., is provided by converters in series in each terminal station, that is, the d.c. rating of each converter is 50 kV, 200 A.

The performance of a valve is determined by the design of its anode assembly, that is, the anode head itself and the intermediate (grading) electrodes which are placed in the path of the arc beneath the anode and all enclosed in a tubular insulator. The latter is located on, and hermetically sealed to, the cathode tank which contains the mercury-pool cathode with its accessories for striking the arcs, etc. and its condensation walls for the mercury vapour. At least with the type of valve designed by Asea, the configuration of the cathode tank has very little effect on the high-voltage behaviour of the valve, the anode assembly being the vital part. Each of the Gotland valves has two of these anodes in parallel, that is to say, the rating of each anode assembly is 100 A at 50 kV. These figures refer to the current and voltage on the d.c. terminals of a complete six-valve group.

The development work on the valves, particularly on their anode assemblies, was carried out in the course of full-scale experiments at the Trollhättan research station run jointly by Asea and the Swedish State Power Board. The experiments were accompanied by continuous design work at Ludvika and by comprehensive investigations into the materials, some of them in co-operation with other manufacturers.

In addition, a team of electronic physicists has been carrying out lengthy and systematic studies of the physical phenomena involved, from the electronics point of view, in the operation of the valve. To begin with, it was difficult to foresee the practical value the theoretical and experimental physical studies would have on practical development work, since physics does not offer any complete theoretical foundation for the discharge phenomena taking place in mercury-arc valves. It is therefore of interest to note to-day that this work has yielded valuable information on several occasions, on which it has been possible to base further experimental progress towards practical and efficient valve designs.



- 1 Transformer
- 2 Mercury-arc valves
- 3 Three-phase a.c. system

Fig. 2. Converter in six-pulse two-way connection. A and B are d.c. terminals.

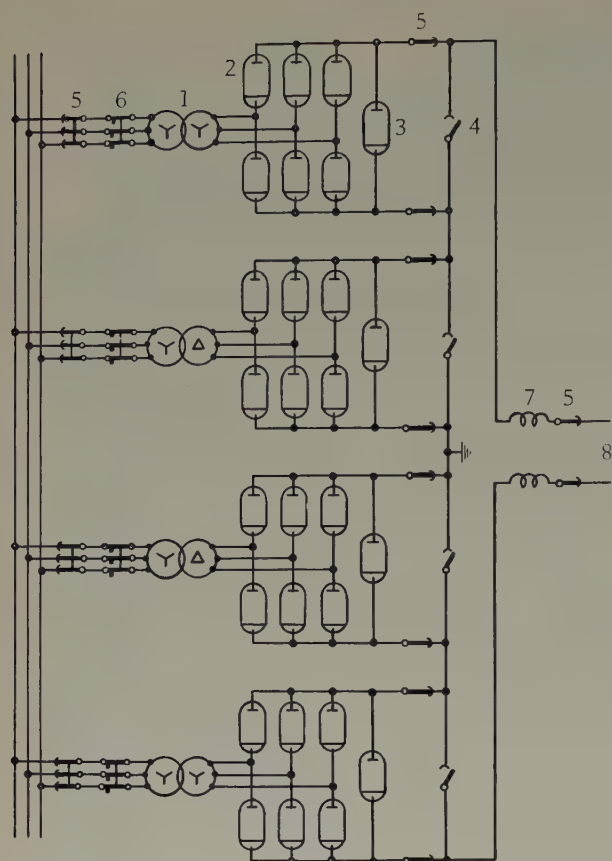
As a measure of the progress that has taken place since the design of the Gotland valve was approved at the beginning of 1953, it may be mentioned that the valves for the Cross-channel project now under construction will have current and voltage ratings per anode which are twice those of the Gotland valves. Since, in addition, each valve has twice the number of anodes, that is to say, four, the power per converter, 100 kV, 800 A, is eight times that of the Gotland converters.

The results of continued experiments at Trollhättan which are being carried out with the object of attaining still higher outputs, show that designs for 125 kV are now a practical proposition and that a further extrapolation to at least 150 kV is within reach using the same design principles. It is also confidently expected that the current value per anode can be increased. However, in the end, the number of parallel anodes per valve will probably be determined on the basis of the economic optimum value.

CONVERTER STATIONS

The terminal stations of a d.c. transmission line differ from normal transformer stations not only in that they have mercury-arc valves and certain other special equipment, but also in that there is a difference in principle in the basic arrangement. In a.c. transformer stations and power-stations, it is general practice to connect in parallel the number of units required to cover the total power of the station. On the other hand, in converter stations, the converter units are connected in series on the d.c. side.

The main reason for this dissimilarity is that it is simplest to connect up or disconnect transformers by means of circuit-breakers, whether the operation is manual or automatic. With d.c., the switching problem is far more difficult and series-connection provides a means of getting around the difficulties. It is of course possible to block the passage of current through a valve group by



- 1 Transformer
- 2 Operating valve
- 3 By-pass valve
- 4 By-pass switch
- 5 Isolator
- 6 Circuit-breaker
- 7 Smoothing reactor
- 8 Outgoing d.c. line

Fig. 3. Converter station with four converters connected in series on their d.c. side.

means of control grids. However, in the case of certain internal faults in the valve, this method is not reliable. On the other hand, it is always possible to take a converter unit connected in series with other converter units out of service merely by means of grid control. This can be done without disturbing the operation of the other units. For this purpose, each valve group is equipped with a "by-pass valve" (Fig. 3) which can short-circuit the d.c. terminals of the blocked converter, thus leading the current past the latter.

Thus, in the case of high-power transmissions, for natural reasons, there will be a number of series-connected converters in each terminal station. It is convenient to have an even number of these and to connect the alternate rectifier transformers in D and Y. This increases the pulse number of the whole station from six to twelve and reduces the ripple and harmonics correspondingly.

Plans have been drawn up for d.c. transmission systems with voltages of up to 400–500 kV between the outer pole and earth. However, study of a number of practical plans of the above type shows that the power has to be divided up over so many converters that the voltage per converter will seldom exceed the 125–150 kV mentioned above. On the other hand, the current strength can always be controlled by selecting an adequate number of anodes connected in parallel in each valve.

Another "heavy" component in the converter station is the d.c. reactor which is often comparable in rating with a converter transformer. It is primarily required at the present stage of development to facilitate fault protection. If a "commutation failure" occurs in an inverter, this means that the d.c. terminals are short-circuited. The object of the reactor is then to limit the rate of increase of the direct current, thus giving the grid control the opportunity of eliminating the disturbance immediately. The time required for this is usually less than one cycle.

It may be of interest to recall that in certain earlier d.c. power-transmission projects, the intention was to depart from the conventional constant-voltage system and to adopt the constant-current system, that is, a system whereby the current is held at the same value while the voltage is allowed to vary with the load. The object was to simplify the fault-protection system.

Modern d.c. transmissions can be said to combine the properties of both systems. Although they normally operate as constant-voltage systems, they change automatically to constant-current systems when faults occur. The entire system of automatic fault-protection is based on this principle and takes advantage of the possibilities offered by grid control.

To return to the d.c. reactor, it may be said that it is also useful as a filter for smoothing the current in the d.c. line. The designing of this filter constituted an intricate electro-mathematical study in which the effective oscillatory circuit formed by the reactor together with the capacitance of the transmission line had to be damped without allowing the power losses to become excessive.

Finally, a further important, and sometimes expensive, component which is to be found, especially in inverter stations, should be mentioned, that is, a generator for the reactive power consumed by the inverter itself and by the a.c. system into which power is fed. In the Gotland scheme, this component consists of a rotating synchronous condenser. However, new methods have been developed making possible, under certain conditions, the use of static capacitors. Thus, the latter are being installed in the converter stations of the Cross-channel

scheme. These capacitors are being connected directly to the 230 kV, a.c. terminals on the French side, but to a tertiary winding in the converter transformers on the British side. This apparatus also acts as a filter and reduces the harmonics generated in the a.c. system by the converters, even though, in most cases, such a reduction is not entirely necessary.

Naturally, the automatic control, regulation and protection devices in a d.c. power-transmission line present many interesting problems. However, in order to limit the scope of the present article, readers are referred to existing publications, for example, those describing the Gotland d.c. transmission system [Asea Journal 27 (1954):10, pp. 141-154]. The requirements made on this installation that it should, alone, be able to supply an entire a.c. network but that, alternatively, it should be able to work in parallel with the power-station, meant that it had to have more complete and advanced control and protection equipment than would be necessary in most high-voltage d.c. transmission systems. Virtually the same apparatus has been used in the Cross-channel scheme, but it was possible, however, to eliminate a number of functions, for example, frequency regulation, thus enabling the equipment to be simplified to a considerable extent [Asea Journal 31 (1958):6, pp. 70-74].

However, it was to the advantage of development work in this sphere that it was necessary, in the very first installation of its kind, to bring out a technique which is likely to be able to cope with the most varying demands which may be expected to be made upon it.

A D.C. POWER TRANSMISSION SYSTEM AS A WHOLE

Since a modern d.c. transmission scheme is always expected to link to a.c. networks, it is of course a valuable property that the networks do not have to be synchronised, and regulation of frequency and power can be determined for each network independently in accordance with the most favourable individual programme. The control panel can, for example, be provided with a handwheel for power settings, and the power set will then be transmitted irrespective of what happens in the two networks. It is also evident that the converters, with their rapidity of control, offer considerable possibilities of varying the control programme. Thus it has been suggested that a d.c. power transmission system should be incorporated as part of the large transmission system, which also comprises a.c. lines, for improving the dynamic stability of the entire system by sending power pulses via the d.c. transmission system to counteract hunting if tendencies in this direction should arise.

Another possibility which the rapidity of control offers is the more rapid elimination of flashovers on the line

insulation. The control and protection methods developed for the Gotland scheme enable the converter station to prevent the rectifier station from sending out a current which is to any extent greater than the current being drained off from the line by the inverter station. Therefore, when flashover occurs on an insulator, the current flowing through the arc is only a fraction of the rated current. The voltage is immediately reduced to zero by means of control measures, the arc is extinguished, and the voltage again taken up to the full value. Since the arc is a "meagre" one and the deionisation period therefore short, and since the grid control works with great rapidity and precision, the total time the transmission is interrupted may be considerably shorter than would be the case in a corresponding a.c. power-transmission scheme fitted with circuit-breakers for rapid auto-reclosing.

OVERHEAD LINES AND CABLES FOR DIRECT CURRENT

It is a well known fact that direct current offers particular advantages as far as submarine or underground cables are concerned, and that, in such cases, the d.c. system becomes economically superior at fairly moderate lengths of line, and, as the distance increases, finally become the only solution technically possible. When direct current is employed, the cable can be considerably simplified and it is expected that, even in the case of voltages higher than the 100 kV of the Gotland cable, a simple, solid-type cable can be used. On the other hand, it is natural that long cables, particularly submarine ones for high power, present many difficult problems as far as manufacture, laying-out and the balancing of design and manufacturing methods against risks and costs are concerned. An important aspect of the choice of the type of cable is, of course, the ease with which it could be repaired should faults arise in spite of all precautions:

There has been considerable discussion during recent years on the employment of plastic material for the insulation and watertight sealing of high-voltage d.c. cables, polyethylene being the main subject of discussion. It would, of course, be tempting to abandon the heavy and relatively weak lead sheathing. However, the situation to-day would appear to imply that certain properties have been found in plastic insulation which make its application dubious at higher voltages than about 100 kV.

Overhead lines for d.c. power transmission have not yet been built. However, projects which are being investigated comprise overhead lines stretching over very great distances. The question of line insulation when direct voltage is used has been studied extensively in Russia, Sweden and in other countries. In these investigations, the question of tracking at normal service voltage caused

by moist deposits of dirt or salt on the insulators has entered the picture and taken on considerable proportions. On the other hand, flashovers due to over-voltages, although they often determine the design of the insulation for a.c. lines, will probably be of minor importance in the case of d.c. transmission lines. This is because of the above-mentioned possibility of rapidly eliminating the effects of flashovers of this kind.

One advantage of the d.c. transmission system which is often mentioned is the possibility of using the earth as a return conductor, thus making the line itself of single-pole design. It is also possible to use a two-pole line with the two poles independent of each other so that the installation can continue to operate at at least half power if a fault should occur on one of the poles since the current would then return through the earth. This earth-return system was adopted with excellent results in the Gotland scheme.

In the Cross-channel project, the shipping authorities have insisted on forward and return conduction of the current through cables in order to obviate the possibility of ships' compasses being influenced. It is probable that, in this case, there has been a tendency towards excessive caution by regarding the maximum compass declination of about 4° which can occur rather than the actual navigational error in miles to which a vessel may be subjected when crossing the cable at a more or less acute angle. The zone in which interference may occur is so narrow that the above-mentioned error in navigation is negligible when compared with other faults which may occur when a vessel is navigating with the aid of a magnetic compass.

Extensive investigations made into the earth-return problem in Sweden during the years 1945–1946 have proved that the electrode current soon penetrates into the interior of the earth and that the currents at the surface are confined to the immediate vicinity of the electrodes without the one electrode influencing the current distribution at the other. It is therefore possible to take full advantage of the experience gained on the effect of ground current produced, for example, by d.c. tramways and railways.

In the case of the latter, the currents are very often considerably higher than those in use in high-voltage d.c. transmission lines and, furthermore, the stray earth currents mainly occur in heavily built-up areas. In view of the greater freedom in locating the earthing electrodes of a d.c. transmission line at a safe distance from cables and other underground objects which may be exposed to detrimental corrosion, as well as the possibility of employing cathodic protection for the objects so endangered, the cases will probably be extremely rare where full use cannot be made of the considerable economic advantages of the earth-return system.

OPERATIONAL EXPERIENCE

When the Gotland scheme was planned, all the participating parties were fully aware of the considerable technical risks involved. In the first place, there was uncertainty as to whether the mercury-arc valves would be able to operate with a satisfactorily low disturbance frequency during prolonged periods of service and as to whether the protection devices which were designed for making undisturbed operation possible, even during arc-backs and other transient disturbance phenomena in the mercury-arc valves, could be made to function satisfactorily as well. Thus, there was no definite opinion on such matters as to whether the boilers in the Gotland power-station should be kept continuously under steam or not in order to provide an immediate standby which, of course, would involve considerable expense.

Now, after over five years service, it is possible to say that, even though teething troubles have been experienced in the auxiliary equipment and have caused service interruptions, the reliability of operation of the transmission has been so good that the above standby measures are not thought to be required. The most critical components, the mercury-arc valves themselves have proved to satisfy service requirements, and the modifications which have been made have been quite trivial. On the whole, it is fair to say that those faults which have occurred are of such a nature that, in future installations, they can be avoided by means of relatively simple measures.

The principles on which control and protection are based will be applied without modification to the Cross-channel project and to any other project in the near future. This is a great advantage in that changes in the mode of operation of equipment of this kind always imply risks of unforeseen initial difficulties.

ECONOMICS

As has been mentioned above, it is difficult to make a general comparison of costs as between various power-transmission systems. Many such comparisons have been attempted in the past, but, until recently, there has always been the difficulty of correctly estimating the cost of the terminal stations when direct current is used. An attempt at comparison was made by F. J. Lane, B. G. Rathsmann, U. Lamm and K. S. Smedsfelt in 1956 in Cigré report 417. It should, however, be noted that the costs for the d.c. alternative here were based on the position as it was assumed to be in the future, when special d.c. equipment, although based on present-day design principles, can be manufactured under approximately the same standard production conditions which apply to-day to conventional a.c. equipment. It should be remembered too that costs vary to a very great extent with fluctuating local conditions.

GERMANIUM AND SILICON RECTIFIERS

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Asea Reg. 490

The principles of construction of germanium and silicon rectifiers are briefly described as well as their general properties. Their cooling, protection, control and service conditions are dealt with as well as different applications, e. g., battery-charging rectifiers, industrial rectifiers and rectifiers for electro-plating.

Asea have manufactured mercury-arc and selenium rectifiers for a considerable time. The advent of germanium and silicon rectifier cells has made possible the building of rectifiers with considerably more favourable characteristics which are suitable for a variety of applications and it has also become possible to use rectifiers for purposes for which they were previously unsuitable. Since the Asea manufacturing programme comprises all types of rectifier, namely mercury-arc, selenium, germanium, and silicon rectifiers, Asea can offer its customers the most suitable alternative for every purpose. This article is intended to present the design of the Asea germanium and silicon rectifiers.

GERMANIUM AND SILICON RECTIFIERS

Fig. 1a shows the basic design of a germanium rectifier cell. A thin germanium disc is soldered to a copper base, and on its upper side the internal terminal is soldered to it with indium. A barrier layer is formed at the junction between the indium and germanium which allows current to flow easily from the indium to the

germanium, but prevents current from passing in the opposite direction. The crystal system is hermetically enclosed. The copper base is designed as a stud and corresponds to the cathode in an electronic valve. The other connection, which corresponds to the anode, consists of a plug on the smaller rectifiers and a flexible connection on the larger ones.

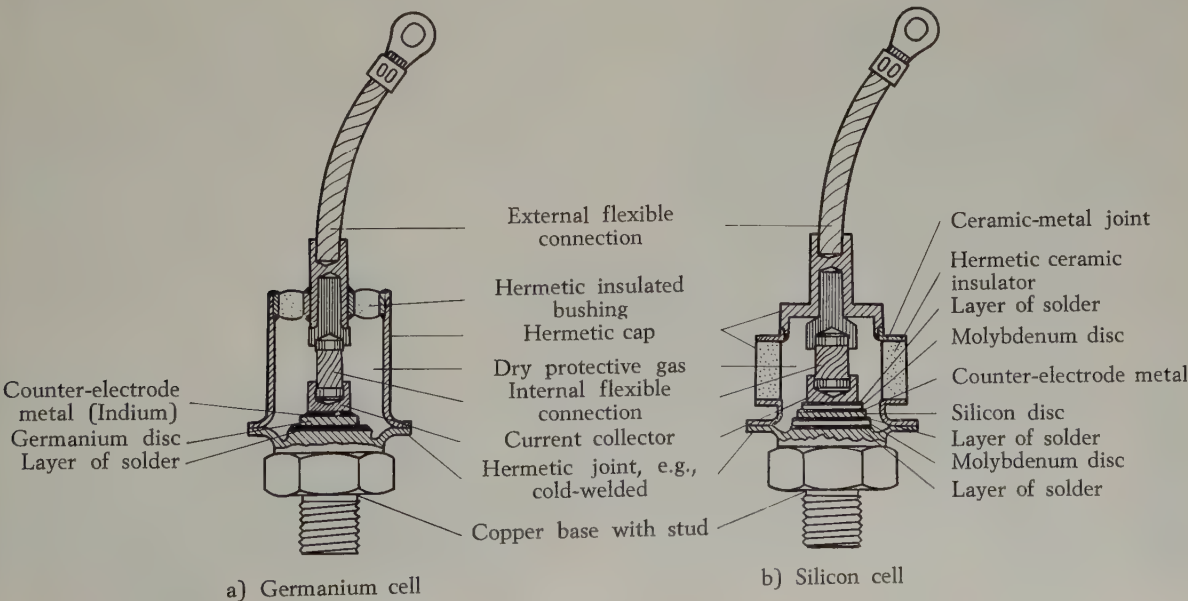
The silicon rectifier cell (Fig. 1b) is designed in accordance with the same principles, but with other materials. However, because of the high operating temperature of the silicon crystal, intermediate layers of molybdenum or tungsten must be introduced in order to eliminate the mechanical stresses which arise because of the differences in thermal expansion.

The characteristics of the two types of rectifier cell can be seen from the following table:

	Germanium cells	Silicon cells
Forward voltage drop (peak value), V	0.5	0.9
Crest working reverse voltage, V	up to 200	up to 600
Crystal temperature, °C	75	140-200
Relative over-current capacity (the ratio between over-current peak value and peak value of the normal current)	10-20	5-15

The values given in the table determine exclusively the choice of rectifier cell. For low voltages, the germanium cell provides better service economy than the silicon

Fig. 1. The construction of germanium and silicon rectifier cells. (Fr 1064)



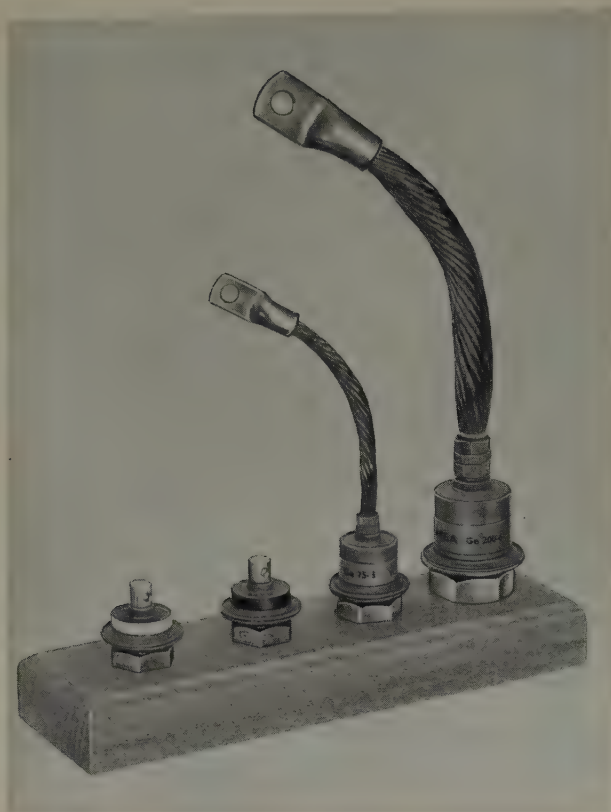


Fig. 2. The Asea standard series of germanium rectifier cells. Rated currents 10, 35, 75 and 200 A. (54202)

cell, if the ambient temperature is normal. At higher ambient temperatures and high direct voltages, above about 100–150 V, the silicon cell is superior, unless, as may occur in certain cases, the over-current capacity justifies the selection of germanium cells. Since, in normal service, the higher permissible temperature for a silicon cell is utilised, it does not give any additional margins. On the other hand, the load on a silicon cell need not be reduced as much as for a germanium cell at high ambient temperatures.

Long-term stability

The germanium and silicon rectifier cells are not affected by ageing. This means that, as distinct from selenium rectifiers, the direct voltage does not change with time.

This enables the design to be simplified and reduces the need for adjustments during the life of the rectifier.

The Asea rectifier cells

Fig. 2 shows the standard series of germanium rectifier cells with rated currents of 10, 35, 75 and 200 A which are manufactured by Asea. Asea is preparing to manufacture silicon cells, but until manufacture is under way silicon cells are being purchased from General Electric Co., U.S.A. Both germanium and silicon cells have proved to have particularly satisfactory performance in service. Cell failures have been so few hitherto that they could only be regarded as isolated occurrences.

An important reason for this satisfactory performance is the thorough tests which each cell has to pass before it is taken into practical use. Among the more important tests, mention can be made of the following:

1. Measurement of the reverse characteristics and voltage drop in order to determine the electrical data.
2. Temperature cycling in order to show up incipient cracks.
3. Pressure tests under water to discover any possible flaws in the encapsulation.
4. Storage at high temperature (long-term thermal stability).
5. Measurement of the reverse characteristics and voltage drop in order to check that these have not changed as a result of the tests.
6. Final electrical grading.

COOLING

The power dissipation in a germanium or silicon rectifier cell takes place in the small crystal and it must therefore be effectively cooled. Next to the crystal this is done by conduction through the copper base and studs which is screwed into a cooling fin or some other type of heat sink. Fig. 3 shows examples of such heat sinks. The smallest cells are usually convection-cooled, while the larger ones are either fan-cooled or, occasionally, liquid-cooled. The arrangement and service conditions of the rectifier are the vital factors when selecting a method of cooling.

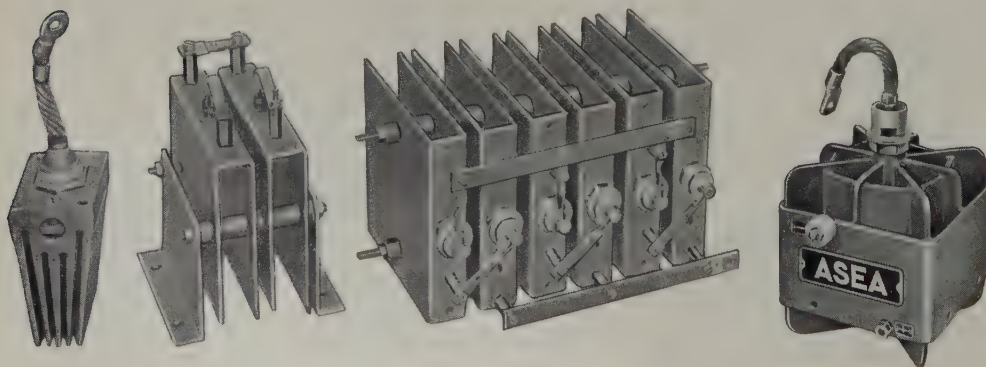


Fig. 3. Examples of various types of heat sink. The smallest rectifier cells are normally self-cooled, while the larger ones have fan cooling and sometimes liquid cooling. (53928, 50656)

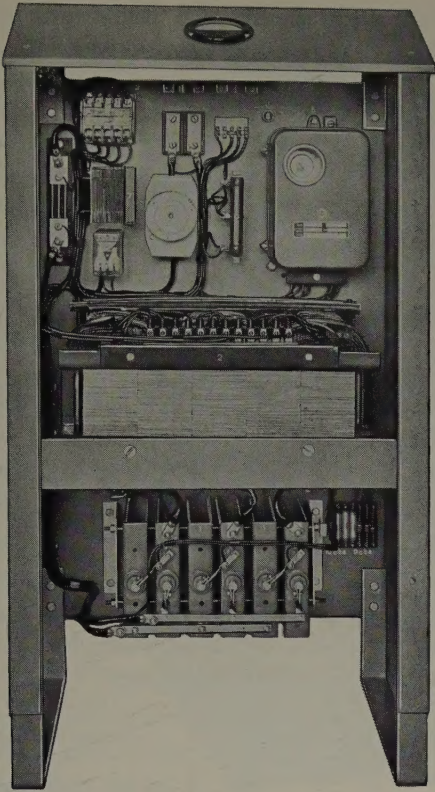


Fig. 4. Battery-charging rectifier for trucks for a nominal battery voltage of 36 V and a charging current of 100 A. The germanium rectifier cells with their cooling fins can be seen at the bottom of the cabinet. (53021)

PROTECTION

Because the crystal and the metallic parts in a rectifier cell are small and the current density high, the rectifier cell is heated very quickly. It is therefore insufficient to protect a semi-conductor rectifier equipment with conventional overload and short-circuit protective devices. Special, extremely rapid protective devices had therefore to be developed, since it would often be too expensive to derate the rectifier cells so much that conventional protective devices could be used.

For small, simple rectifiers, specially developed high-speed fuses provide adequate protection against external and internal short circuits. They are usually located one in each phase or each leg of the rectifier connection depending on the load conditions. Fuse protection against external faults is only suitable where these faults occur very seldom and where service conditions are easy, since changing fuses is always expensive and time-wasting.

In the case of larger units, from about 10 kW up to about 100 kW, the protection is supplemented by conventional means, for example, normal over-current relays with independent time-lag characteristic so that moderate over-currents do not blow the fuses, but trip the line circuit-breaker instead. The rectifier can then

rapidly be reset for normal service. If the rectifier has several cells connected in parallel in each leg, the protection can be arranged in such a way that each cell itself is protected individually in order to limit the damage which might occur in the event of a fault in one cell. Protection against d.c. short circuits is arranged by placing in the d.c. busbar a fuse which is co-ordinated with the fuses of the cells in such a way that the latter are not affected by a d.c. short circuit.

In installations where short circuits are usual, for example, in the case of rectifiers for supplying mine railways, the use of fuses is not suitable because of the expense and the time lost when changing them. Asea have therefore designed a small and inexpensive short-circuiting device for low ratings. It trips in about 2 milliseconds and then switches the short circuit over to the a.c. side of the rectifier at the same time as it provides tripping impulse for the primary circuit-breaker. When the short circuit on the d.c. side has been removed, the rectifier can again be taken into service by means of two simple manual operations.

Installations in which extremely high demands are made upon service reliability are designed with more rectifier cells in parallel than would be required for the rated data, in spite of the fact that cell faults are very few. One or two rectifier cells can therefore be permitted to go out of service without having to stop the installation for changing cells, and this operation can, instead, be carried out on a suitable occasion.

As protection against d.c. short circuits in large installations (of the order of size of megawatts) use is made of an a.c. circuit-breaker, short-circuiting device, trans-

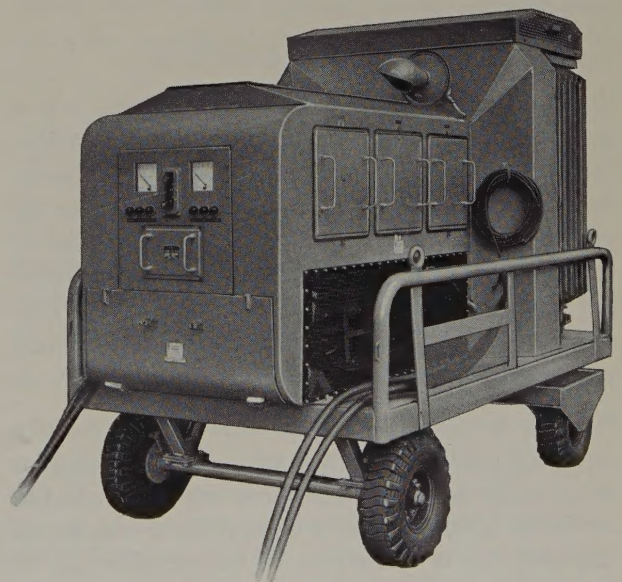


Fig. 5. An industrial rectifier which is reconnectible between 220 V, 1,000 A and 110 V, 2,000 A. (52618)

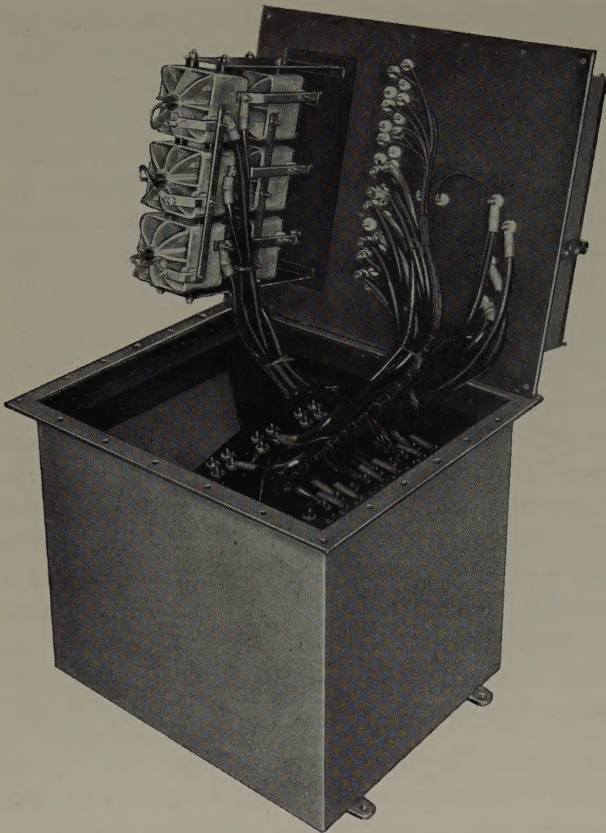


Fig. 6. Rectifier for supplying current to the lifting-magnet of an overhead travelling crane. The rectifier is totally enclosed and the rectifier cells are placed on cooling fins immersed in the transformer oil. (53571)

ductor, or a combination of these. The system selected depends upon the type of short circuit which may occur, and this is, in its turn, connected with the voltage, the arrangement of the installation, parallel operation, if any, the characteristics of the supply network, etc.

VOLTAGE AND CURRENT CONTROL

Voltage control in order to eliminate a voltage drop is not often required for germanium and silicon rectifiers. On the other hand, in many cases, the effect of variations in the supply network must be eliminated. For the smaller rectifiers, Asea make use of the transductor technique which was developed for selenium rectifiers and which has proved very satisfactory in service. These control equipments have been simplified to a very great extent during the years.

For large installations, it is economic to make use of a regulating transformer with a tap changer having relatively small steps for the coarse regulation. If fine regulation is required, this is brought about with the aid of a new type of transductor on the secondary side of the transformer. This transductor, which only has to absorb a small part of the voltage, gives a negligible switching surge and does not affect the power factor

to any noteworthy extent. The insulation of the transductor is of dry type and the device is placed in the rectifier cabinet where it takes up very little room.

For automatic control of the tap changer and transductor, Asea have developed a system which makes possible control at a constant voltage or current. The motor operation of the tap changer is made dependent on the working point of the transductor.

LOAD CLASSIFICATION

As has been mentioned above, it is of decisive importance that a germanium or silicon rectifier should also be designed for the short-time loads to which it will be exposed during service. It is often difficult to anticipate these, but it has been possible, on the basis of experience, to quote a number of different rating classes which give stresses corresponding to those which arise during actual service. Normally, Asea design rectifiers for one of the following rating classes:

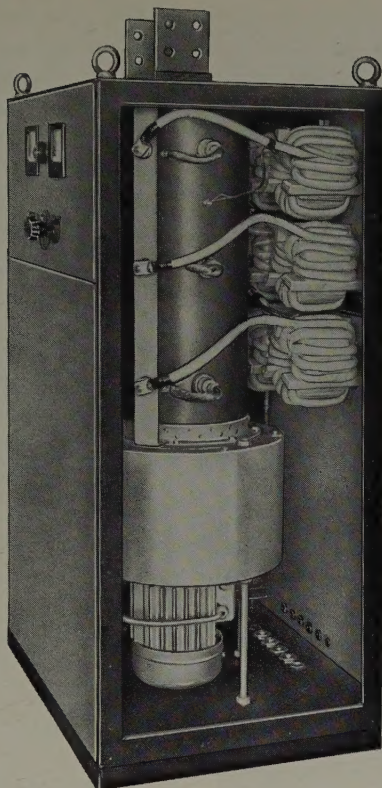
Class	Application	Rectifier designed for
A	Electro-plating, lifting-magnets, electro-chemical service	100 per cent continuous without overloading
B	Light industrial service, very light motor service	100 per cent continuous and with rectifier at service temperature 125 per cent for 15 min. 150 per cent for 2 min. 200 per cent for 10 s
C	Heavy-duty industrial service, normal motor service, mine railways	100 per cent continuous and with rectifier at service temperature 125 per cent for 2 hours 200 per cent for 1 min.
D	Extra-heavy-duty motor service, tramways	100 per cent continuous and with rectifier at service temperature 150 per cent for 2 hours 300 per cent for 1 min.

On request, the rectifiers can also be designed for other service conditions.

BATTERY-CHARGING RECTIFIER EQUIPMENTS FOR TRUCKS

An essential requirement in a battery-charging rectifier intended for trucks is that its current-voltage characteristics should be such that, for a limited period, it supplies the battery with a certain determined charge. The relatively high voltage drop in the selenium plates meant that a transductor was needed in order to obtain a suitable characteristic. When using germanium rectifier cells, it is possible, however, to achieve satisfactory results with a leakage-flux transformer. Fig. 4 shows a rectifier of this kind for a nominal battery voltage of

Fig. 7. A transducer-controlled germanium rectifier unit for electro-plating, rated at 8 V, 1,000 A. On the extreme right, the six transducer elements can be seen and, immediately to the left of these, three of the six germanium rectifier cells which are mounted on the cooling ducts are visible. (53934)



36 V and a charging current of 100 A. The germanium rectifier cells with their cooling fins can be seen at the bottom of the cabinet.

Since, here, the leakage-flux transformer limits the current, protection for the rectifier cells is unnecessary. On the other hand, a normal fuse is used in the d.c. conductor in order to provide protection against short-circuiting of the battery. A series of rectifier equipments with various ratings designed in accordance with this principle is kept in stock.

INDUSTRIAL RECTIFIERS

Fig. 5 shows another example of a semi-conductor rectifier equipment. It is reconnectable between 220 V, 1,000 A and 110 V, 2,000 A. The equipment is intended to supply direct current for industrial purposes. The direct current is divided up over a number of outgoing cables, each of which is fitted with a fuse having a rated current considerably lower than that of the rectifier.

CORRECTION

It was erroneously stated in our article on the Rapide Blanc Power-station, Canada, which appeared in the Asea Journal 33(1960):3, pp. 40-42, that the Shawinigan Engineering Company exploited the hydro-electric resources of the River St. Maurice, Quebec, and owned power-transmission lines in this area. The company to which we were referring is, in fact, the Shawinigan Water and Power Company Limited, and not the one mentioned above. In this connection, we

Fig. 6 shows another industrial rectifier. It is intended for supplying current to the lifting-magnet of an overhead travelling crane and it has to operate in dusty premises for which reason it was necessary to make the rectifier of totally enclosed design. In order to cool the transformer, oil has to be used and this is also used for cooling the rectifier cells which are placed direct on cooling fins immersed in the transformer oil. The temperature of this oil is determined by the transformer, and by selecting silicon rectifiers it was possible to work with relatively high temperatures, thus giving small dimensions and a good utilisation of the transformer.

In this case, short circuits on the d.c. side occur only when there is a fault on the connections from the rectifier to the lifting-magnet, and since each arm contains only one rectifier cell, it has been considered justified to use common fuses for cell faults and external short circuits. For this purpose, three high-speed fuses have been inserted in the phase conductors.

RECTIFIERS FOR ELECTRO-PLATING

Fig. 7 shows a transducer-controlled germanium rectifier for electro-plating. The germanium rectifier cells with their cooling fins are located in an air duct through which air is drawn down by means of a centrifugal fan which then blows the air on to the transformer and the transducers. Since the air is drawn in at the top, dust and dirt from the floor do not enter the rectifier.

Transducer control has great advantages when compared with more conventional methods. The entire control system is built up of static components without moving parts, for example moving contacts, and this results in good reliability. The rectifier is made with avostat control, thus making it proof against short circuits, which is of considerable value in electro-plating installations.

It is easy to arrange remote control of the rectifier since only very small amounts of power are required for this purpose. Thus, motor operation or other complicated devices do not need to be adopted.

A series of rectifiers has been designed for the currents and voltages which are normal in electro-plating. They are all built up in virtually the same way.

should also like to mention that the map of power lines in Fig. 2 on page 41 in the above number was drawn on the basis of an out-of-date original and thus does not show the 230 kV lines south of the St. Lawrence which are now being operated by the Shawinigan Water and Power Company. It was most unfortunate that these two errors should have appeared in our article and we should like to offer our most sincere apologies.



(Z 11371)

NEWS IN BRIEF

THE SWEDISH STATE POWER BOARD AND ASEA SIGN THEIR BIGGEST CONTRACT

On 15th June, 1960, the Swedish State Power Board signed the biggest contract in its history. The other party was Asea and the agreement concerns the manufacturing of the greater part of the R3/Adam nuclear reactor for the Ägesta power-station near Stockholm [see the Asea Journal 31(1958):6, pp. 81-82 and 32(1959):6, pp. 76-77] and the erection of the entire reactor and its auxiliary equipment. The value of the contract is about Mkr 40 (about £ 2,800,000) and the agreement was signed on behalf of the Power Board by its Director-General, Mr Erik Grafström, and by Mr Ingvar Wivstad, Head of the Atomic Power Department, and on behalf of Asea by the Managing Director, Dr Åke Vrethem, and by Dr Halvard Liander and Dr Curt Mileikowsky. The illustration shows Dr Vrethem (left) shaking hands with Mr Grafström after the signing of the contract. Mr Wivstad is seated at the table.

A supplementary agreement was recently reached between AB Atomenergi (the Swedish Nuclear Energy Authority) and Asea.

The Ägesta power-station is to be built by AB Atomenergi, the Swedish State Power Board and the Stockholm Electricity Authority. AB Atomenergi is responsible for the broad outlines of the design, while Asea are responsible for the detailed design, and for manufacture and erection, as well as being the main contractor for the reactor and its auxiliary equipment. Asea have agreed to carry out the work at cost price. The erection of the equipment is to start at the beginning of next year.

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